United States
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ARS-30

April 1985

Proceedings of the Natural Resources Modeling Symposium

Pingree Park, CO
October 16-21, 1983

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Cover Photograph: The Pingree Campus of Colorado State University is located west of Fort Collins, at the foot of the Mummy Range. Its boundaries are the Roosevelt National Forest, the Comanche Peak Wilderness Area, and the Rocky Mountain National Park.

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Donn G. DeCoursey
Editor

PREFACE

In the last few years, scientists in the Agricultural Research Service, ARS-USDA, have developed several mathematical models of field and small watershed response. The models have simulated the hydrologic, erosion, crop growth, and water quality characteristics representative of various land use and treatment scenarios. Most of the model development was in response to needs of the Soil Conservation Service (SCS); regulatory agencies, such as the Environmental Protection Agency (EPA); and other action agencies. In some cases, models have been developed to aid research programs by providing an analytical description of the physical processes being investigated.

Recent model development has been rapid; it involves many disciplines and requires scientists from different backgrounds to work together. The Symposium was structured as a forum within which scientists could discuss the technical aspects of their work and compare ideas. It also provided the Soil Conservation Service an opportunity to learn more about the models that are being developed and an opportunity to describe what they need.

The first part of the symposium, about two and one-half days, presented an overview of various ARS modeling and related programs and SCS efforts to incorporate them into their programs. The second part of the symposium, about one and one-half days, consisted of four concurrent sessions: chemical and biological processes, soil-water-plant relations, hydrology, and erosion. Presentations in the four concurrent sessions were selected to present the state-of-the-art and research needs as they exist in ARS and SCS.

The symposium was jointly sponsored by ARS and SCS to--

1. Improve coordination of ARS and SCS model development activities.
2. Develop an understanding of SCS model development priorities and research needs.
3. Improve coordination of ARS natural resource research programs.
4. Present the state of the art in concepts and models and emphasize the need to expand ARS research to related disciplines.
5. Within the context of the ARS Program Plan, SCS research needs, and the priorities established in the SCS Information Resources Management Long Range Plan, identify the highest priority research needs, tasks to be accomplished, and individuals or locations that could carry out the tasks.
6. Identify existing research data sets that should be assembled and incentives to encourage their development. Identify new research data sets that should be developed, what they should include, and how extensive they should be.
7. Define the data bases, both geographically referenced data and attribute data that will be required to make the models operational. Identify sources of available data, nonexistent data, and the most critical needs for model use.

Coordinators for the Symposium were Donn G. DeCoursey, ARS-Fort Collins, CO, and John Okay, SCS-Washington, D.C. They wish to express their thanks to the staff of the ARS Hydro-Ecosystem Research Unit responsible for organizing and conducting the Symposium and to Colorado State University and the Pingree Park Staff for use of their facilities. Success of the Symposium belongs to the participants who attended, made presentations, participated in discussions during the symposium, and prepared these written summaries of their material. The coordinators sincerely appreciate the interest, enthusiasm, and discussion by participants, especially those from other agencies.

Donn G. DeCoursey, editor
Fort Collins, CO

NATURAL RESOURCES MODELING SYMPOSIUM

AGENDA

GENERAL SESSION

Coordinators: J. Okay, D. G. DeCoursey

Monday October 17, 1983 — Moderator: D. G. DeCoursey

A.	Introductory Comments (8:00 - 9:05)	
	1. Announcements and Introductions (15)	D. G. DeCoursey
	2. Welcoming Comments by ARS (30)	J. M. Vetterling H. C. Cox S. L. Rawlins
	3. Welcoming Comments by SCS (20)	G. Comer P. Howard
B.	Agency Response to Model Development (9:05 - 11:15)	
	1. Model Development and Application (40)	F. D. Theurer
	2. Soil and Water Conservation Assessment Model (SAWCAM) (20)	G. Comer
	3. An Important Step-Technology Transfer (20)	D. Ralston
	4. Changes in Agricultural Research (20)	A. R. Grable
	Break (30)	
C.	ARS Model Overviews (11:15 - 12:00)	
	1. Simulation for Water Resources in Rural Basin (SWRRB) (45)	
	Presentation	A. D. Nicks
	Discussion	E. C. Nicholas
	Lunch (12:00 - 1:00)	
D.	ARS Model Overview (1:00 - 5:00)	
	1. Erosion/Productivity Impact Calculator (EPIC) and Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) (1:45)	
	Presentation	J. R. Williams, C. A. Jones, P. T. Dyke
	Discussion	R. Grossman
	Break (30)	
	2. Chemicals, Runoff, and Erosion of Agricultural Management Systems-latest version (CREAMS II) (1:45)	
	Presentation	W. G. Knisel, R. E. Smith
	Discussion	J. N. Krider

Tuesday, October 18, 1983	Moderator: G. Comer
A. ARS Model Overview (8:00 - 12:00)	
1. Small Watershed Model (SWAM) (1:45)	
Presentation	D. G. DeCoursey, C. V. Alonso
Discussion	B. Shafer
Break (30)	
2. Simulation of Production and Utilization of Rangelands (SPUR) (55)	
Presentation	J. R. Wight
Discussion	D. Pendleton
3. Wind Erosion (50)	
Presentation	G. W. Cole
Discussion	D. Pendleton
Lunch (12:00 - 1:00)	
B. ARS Model Overview (1:00 - 5:00)	
1. Soil, Plant, Air, Water (SPAW) Model (50)	
Presentation	K. E. Saxton
Discussion	G. Darby
2. Nitrogen, Tillage, Residue Management (NTRM) Model (55)	
Presentation	M. J. Shaffer
Discussion	G. Darby
Break (30)	
3. Crops and Soil Simulation (1:45)	
A Systems Approach to Soils Research	V. C. Cole, R. D. Heil
A General Overview of Crop Simulation	D. N. Baker
A General Overview of Root Modeling	M. G. Huck
Discussion	A. Hidlebaugh

Wednesday, October 19, 1983	Moderator: D. G. DeCoursey
A. ARS Model Overviews (8:00 - 11:00)	
1. Remote Sensing (55)	
Presentation	A. Rango
Discussion	S. Robbins
2. Hydrologic Classification of Soils (50)	
Presentation	W. J. Rawls, D. L. Brakensiek
Discussion	S. Robbins
Break (30)	

3. Data Base Development (45)
    - Site Specific Automated Data Management and Retrieval — C. R. Amerman
    - Data Bases for Model Development and Testing, An Example — D. G. DeCoursey
    - Assembly in a Data Bank — J. B. Burford
    - Organization of National Data Bases for Use in Process Models — P. T. Dyke, W. Fuchs, G. Wistrand
    - Data Base Technology — A. D. Nicks, G. C. Bluhm
    - Use of Artificial Intelligence — K. G. Renard

B. Challenge to Concurrent Sessions (11:00 - 11:15) — J. Welsh

C. Break and Reassemble into four concurrent sessions (11:15 - 11:25)
At 11:25
1. Chemical and Biological Processes
2. Soil-Water-Plant Relationships and Economics
3. Hydrology
4. Erosion and Sedimentation

Friday, October 21, 1983 — Moderator: J. Okay

A. Report of Concurrent Sessions (8:00 - 10:00)
1. Chemical and Biological Processes — R. F. Follett, H. B. Pionke, C. Thomas
2. Soil-Water-Plant Relationships and Economics — A. R. Grable, K. E. Saxton, A. Hidlebaugh
3. Hydrology — M. E. Jensen, D. L. Brakensiek, R. Rallison
4. Erosion and Sedimentation — D. A. Farrell, K. G. Renard, W. Mildner

Break (30)

B. Wrap-Up (10:30 - 12:00)
1. Comments by participants from visiting agencies
2. Comments from SCS
3. Comments from ARS

Items to be Considered in Concurrent Session Discussion Periods

1. Evaluate the range of applicability of the material discussed.
    a) Limits, restrictions, strengths and weaknesses, size of area, etc.
    b) If applicable, what is necessary to apply to irrigated area?
2. What kind of data sets are needed for testing, validation and further development?
3. In the context of the ARS Program Plan, what are the highest priority needs, how long will it take, and who or what locations should consider the research?
4. Chairpersons should summarize the results of the discussion so that it can be made available to all participants as a guide to improved coordination and direction of research.
5. To get familiar with the models.

NATURAL RESOURCES MODELING SYMPOSIUM

AGENDA

CONCURRENT SESSION I - Chemical and Biological Processes
Chairpersons: R. F. Follett, H. B. Pionke, C. Thomas

<u>Wednesday, October 19, 1983</u>

A.	Challenge to Participants (11:25 - 12:00)	
	1. SCS Overview	D. Marriage
	2. ARS Overview	R. F. Follett

<u>Lunch</u> (12:00 - 1:00)

B.	Phosphorus (1:00 - 3:30)	Moderator: C. Thomas
	1. Dynamics of Phosphorus Cycling in Soil (30)	V. Cole
	2. Use of Sorption Isotherms to Characterize Stream Transport of P in Watersheds (20)	H. Kunishi, H. Pionke
	3. Soil and Water Properties Affecting EPC (20)	R. Wendt
	4. The Role of Desorption Kinetics in Modeling the Transport of Adsorbed Chemicals (20)	A. Sharpley, L. Ahuja H. Pionke
	5. Estimation of Phosphorus Parameters for Modeling from Limited Soil Survey Information (20)	A. Sharpley, V. Cole, C. A. Jones
	6. Relationship between Labile P and Soil P Test Values (20)	A. Wolf, D. Baker, H. Pionke, H. Kunishi
	7. Discussion[1] (20)	

<u>Break</u> (3:30 - 4:00)

C.	Salts and Major Ions (4:00 - 5:00)	Moderator: C. Thomas
	1. Prediction of Major Ion Concentrations in Arid Land Soils Using Equilibrium and Kinetic Theories (40)	D. Suarez
	2. Discussion[1] (20)	

<u>Thursday, October 20, 1983</u>

D.	Pesticides (8:00 -	Moderator: H. B. Pionke
	1. Microbes and Microbial Population Dynamics as Related to Pesticide Degradation in Soil (30)	P. Kearney

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[1] See description of items to be discussed at end of the agenda for the General Session.

2. Pesticide Dissipation Rates from Farm Ponds and Small Impoundments (20) — R. Nash, A. Isensee
3. Methods of Estimating Pesticide Adsorption/Desorption Coefficients (20) — R. Green
4. Pesticides in Surface Irrigation Runoff Water (20) — W. Spencer
5. Discussion (30)

Break (10:00 - 10:30)

E. Nitrogen (10:30 - 12:00) — Moderator: H. B. Pionke

1. Dynamics of Nitrogen Cycling in Soil (30) — W. Parton, L. Porter
2. Modeling of Microbial Population and Activity on NO_3 Production, Mineralization, Immobilization and Denitrification in Soils (20) — W. Caskey, J. Schepers
3. The Organic N/Organic-C Relationships and Estimating the Parameter for the NH_4 Sorption Isotherm (20) — R. Schnabel
4. Discussion[1] (20)

Lunch (12:00 - 1:00)

F. Models (1:00 - 3:30) — Moderator: R. F. Follett

1. Leaching Green Crops and Their Residues as a Source of Nutrients in Agricultural Runoff (20) — J. Schreiber
2. EPIC - The Nutrient Models (20) — C. A. Jones, A. Sharpley, V. Cole
3. CREAMS II - The Nutrient and Pesticide Models (20) — R. Leonard
4. SWAM - The Nutrient, Pesticide and Biological Models
   a) Chemical Models Used in the Channel System (20) — H. Pionke, H. Kunishi, R. Schnabel, R. DeAngelis, C. Alonso
   b) Modeling Chemical and Biological Processes in Agricultural Impoundments (20) — C. Galleges, R. Menzel, A. Sharpley
   c) Hydrology and Nutrient Considerations for Wetlands (20) — J. C. Lance

   Discussion[1] (30)

Break (3:30 - 4:00)

G. SCS Response (4:00 - 5:00) — Moderator: R. F. Follett

1. Reactions and Suggestions Regarding the Presented ARS Chemical-Biological Models and Modeling Approaches (60) — C. Thomas, et al.

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[1]See description of items to be discussed at end of the agenda for the General Session.

NATURAL RESOURCES MODELING SYMPOSIUM

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CONCURRENT SESSION II - Soil-Water-Plant Relationships
Chairperson: A. R. Grable, K. E. Saxton, A. Hidlebaugh

Wednesday, October 19, 1983

A. Challenge to Participants (11:25 - 12:00)
   1. SCS Crop Modeling Needs — A. R. Hidlebaugh
   2. ARS Overview — A. R. Grable

   Lunch (12:00 - 1:00)

B. Current Use of Crop Models in Resource Management (1:00 - 5:00) — Moderator: A. Hidlebaugh
   1. CREAMS II (30) — R. E. Smith
   2. EPIC-ALMANAC (30) — J. R. Williams, A. Jones
   3. SPAW (30) — K. E. Saxton

   Break (30)

   4. NTRM (60) — M. J. Shaffer, D. Linden, S. Gupta
   5. SPUR (30) — J. Hansen, J. Skiles, W. Parton
   6. Discussion[1] (30)

Thursday, October 20, 1983

C. Developments in Soil and Crop Modeling (8:00 - 12:00) — Moderator: K. E. Saxton
   1. Overview of Modeling Crops (30) — D. N. Baker
   2. Overview of Modeling Roots (20) — M. G. Huck
   3. An Overview of Modeling Nutrient Cycling (30) — V. C. Cole
   4. Overview of Modeling Soil Physical Processes (30) — F. D. Whisler

   Break (20)

   5. ET and Soil Water Properties - Panel (30) — W. J. Rawls, K. E. Saxton, K. R. Cooley, W. J. Parton, R. Grossman

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[1] See description of items to be discussed at end of the agenda for the General Session.

6. Remote Sensing Inputs for Crop Models - Panel (30) — C. L. Weigand, P. R. Nixon, R. D. Jackson, A. Rango

7. Interfacing Crop and Resource Management Models - Panel (30) — M. J. Shaffer, D. A. Christiansen et al.

8. Discussion[1] (20)

Lunch (12:00 - 1:00)

D. Future Directions and Priorities in Crop Modeling for Resource Management (1:00 - 5:00) — Moderator: A. R. Grable

1. Work Groups (2 hours)
    a) Water Management - Runoff; ET; irrigation scheduling; drainage needs; water allocations — Leader: J. Hatfield
    b) Soil Management - Erosion control; tillage needs; assessment of drainage, salinity, compaction, soil fertility, soil temperatures — Leader: W. O. Willis
    c) Crop Management - Biomass and crop production; ground cover and residue decomposition; use of fertilizers and pesticides; assessment of weather and air quality effects; seedling establishment — Leader: E. L. Klepper
2. Discussion of interactions and preparation of report on priority research and development needs (2 hours).

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[1] See description of items to be discussed at end of the agenda for the General Session.

NATURAL RESOURCES MODELING SYMPOSIUM

AGENDA

CONCURRENT SESSION III - Hydrology
Chairperson: M. E. Jensen, D. L. Brakensiek, R. Rallison

Wednesday, October 19, 1983

A. Challenge to Participants (11:25 - 12:00)
   1. SCS Overview (to be presented in following session)
   2. ARS Overview — M. E. Jensen

Lunch (12:00 - 1:00)

B. Model Input: Data requirements, accuracy and representation of spatial and temporal variability (1:00 - 2:45) — Moderator: D. G. DeCoursey
   1. SCS Overview on Spatial Variability (15) — S. Robbins
   2. ARS Overview on Spatial Variability (15) — R. E. Smith
   3. Modeling Watershed and Climate Variability (75)
      a) Characterizing watersheds — A. S. Rogowski, M. Sharma
      b) Climatic data generators — C. W. Richardson, A. D. Nicks
      c) Stochastic rainfall models — D. A. Woolhiser, H. Osborn
      d) Discussion[1]

Break (2:45 - 3:00)

C. Water Supply Forecasting Snowmelt Routines; real time data input and outputs; forecast accuracies; and user requirements (3:00 - 5:00) — Moderator: R. Rallison

[1] See last page for items to be discussed.

1. Water Supply Modeling (40)
    a) SCS water supply forecasting — B. Shafer
    b) Cooperative research on water supply forecasting — K. Cooley
    c) Discussion[1]
2. Snowmelt Modeling (45)
    a) CREAMS II — R. E. Smith
    b) SPUR — K. Cooley
    c) SRM — A. Rango
    d) Discussion[1]
3. Frozen Soil Modeling (30) — K. Cooley
    a) Discussion[1]

Thursday, October 20, 1983

D. Surface Water Modeling: Model components; input requirements; output options; physical and numerical accuracy; and management applications (8:00 - 12:00) — Moderator: D. L. Brakensiek
1. SCS Overview of Operational Options (15) — N. Miller
2. ARS Overview of Surface Water Modeling (15) — D. G. DeCoursey
3. Runoff Models (30)
    a) CREAMS II — R. E. Smith
    b) Discussion
4. Infiltration Models (60)
    a) CREAMS II — R. E. Smith
    b) Parameters — W. J. Rawls, D. L. Brakensiek
    c) Surface sealing — L. R. Ahuja
    d) Chemical effects — D. L. Suarez
    e) Discussion[1]

Break (10:00 - 10:15)

5. Channel Flow Models (60)
    a) SWAM — C. V. Alonso
    b) CREAMS II — R. E. Smith
    c) SWRRB — J. R. Williams
    d) SPUR — L. J. Lane
    e) Surface irrigation — A. J. Clemmens
    f) Discussion[1]

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[1]See last page for items to be discussed.

6. Water Quality (40)
    a) Impoundments — C. Galleges, F. R. Schiebe
    b) Temperature — F. Theurer
    c) Discussion[1]

Lunch (12:00 - 1:00)

E. Subsurface Water Modeling: Model components; input requirements; output requirements; model fidelity and numerical accuracy; management applications; and time scale requirements (1:00 - 5:00) — Moderator: M. E. Jensen

1. SCS Overview (15) — P. Lucas
2. ARS Overview (15) — C. R. Amerman
3. Unsaturated-Saturated Flow Models (15) — E. P. Springer
4. ET Models: Overview (30) — J. Hatfield
    a) Discussion[1]
5. Drainage Models (45)
    a) Drainmod — R. W. Skaggs, J. L. Fouss
    b) Seepage — J. W. Naney
    c) Interceptors — R. E. Smith
    d) Discussion[1]

Break (3:00 - 3:15)

6. Sub-Irrigation/Water Management Models (30)
    a) Drainmod — J. L. Fouss
    b) District Water Management — J. E. Parsons
    c) Discussion[1]
7. Groundwater Models (50)
    a) SWAM — D. G. DeCoursey
    b) Soil water and chemical process — D. L. Suarez
    c) Recharge — R. E. Smith
    d) Discussion[1]
8. Mass Transport Models: Overview (25) — M. J. Shaffer
    a) Discussion[1]

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[1] See last page for items to be discussed.

Objectives of the Hydrology Session are to:

1. Identify and review available subroutines that are being used for the major hydrologic components in existing models. Group by input data requirements and output data, and by testing requirements;

2. Order each of the main subroutines in two or three levels of: a) probable accuracy for various time periods; and b) input data required to drive the subroutine or model;

3. Evaluate the adequacy of existing subroutines and models to provide specific needed hydrologic components for natural resource models that are being developed and for user applications;

4. Identify how remote sensing may be used with a subroutine or model to increase its accuracy and to facilitate its use to obtain real time data for user purposes.

Presentations should be focused on session objectives and not solely a description of models, many of which have already been summarized adequately.

Discussion periods will be used to reach a concensus on which subroutine or model to use for specific levels of accuracy and available input data consistent with applications, and to generate input from SCS persons on their operational needs to be tied with present models. Highest priority research needs should be identified with reference to the ARS Program Plan (6-year Implementation Plan). Also, where and how priority research can most effectively be conducted consistent with the 6-year Implementation Plan should be identified.

NATURAL RESOURCES MODELING SYMPOSIUM

AGENDA

CONCURRENT SESSION IV - Erosion and Sedimentation
Chairpersons: D. A. Farrell, K. G. Renard, W. Mildner

Wednesday, October 19, 1983

A.	Challenge to Participants (11:25 - 12:00)	
	1. Introductory Remarks (5)	K. G. Renard
	2. SCS Overview (15)	D. G. Burns, D. E. Hawkins
	3. ARS Overview (15)	D. A. Farrell
	Lunch (12:00 - 1:00)	
B.	Source Area Erosion Processes (1:00 - 5:00)	Moderator: D. A. Farrell
	1. Introductory Remarks (5)	D. A. Farrell
	2. SCS Issues and Concerns (10)	K. Flach
	3. Deposition and Transport of Sediments (25)	W. H. Niebling, G. R. Foster
	4. Modeling Erosion and Deposition (25)	R. Khanbilvardi, A. S. Rogowski
	5. A Dynamic Erosion Concept (25)	G. R. Foster, R. E. Smith
	6. Tillage and Residue Effect on Erosion from Croplands	J. M. Laflen
	Break (15)	
	7. Weathering Effects on Soil Erodibility (25)	D. K. McCool, R. A. Young
	8. T-Values (30)	K. Flach
	9. Remote Sensing and Erosion (informal) (25)	J. C. Ritchie
	10. Discussion[1] (30)	

Thursday, October 20, 1983

C.	Erosion Assessment (8:00 - 12:00)	Moderator: K. G. Renard
	1. Introductory Remarks (5)	K. G. Renard
	2. SCS Issues and Concerns (10)	G. Darby
	3. Systematic Prediction of Wind Erosion - Phase I (25)	G. W. Cole

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[1]See description of items to be discussed at end of the agenda for the General Session.

4.	Factors Affecting Furrow Erosion (25)	W. D. Kemper
5.	Furrow Erosion Prediction (25)	N. M. Curtis
6.	Structural Measures to Control Erosion (25)	W. K. Twitty

Break (15)

7.	Seasonally Ephemeral Gully Erosion (25)	G. W. Foster, L. J. Lane
8.	Rangeland Erosion (25)	C. W. Johnson, K. G. Renard, G. W. Foster
9.	Replacing the USLE - Panel Discussion (30)	G. W. Foster, C. V. Alonso, J. M. Laflen
10.	Discussion[1] (30)	

Lunch (12:00 - 1:00)

D. Gully Erosion and Sedimentation Processes (1:00 - 5:00) — Moderator: W. Mildner

1.	Introductory Remarks (5)	W. Mildner
2.	SCS Issues and Concerns (10)	W. Mildner
3.	Modeling of Large Gullies (30)	N. L. Coleman, F. R. Schiebe, A. W. Thomas
4.	Channel Erosion (30)	N. L. Coleman
5.	Sediment Distribution in Reservoirs	F. R. Schiebe

Break (15)

6.	Routine Sediment in Stream Channels (30)	C. V. Alonso
7.	Sediment Routing in SWRRB (30)	J. R. Williams
8.	Sediment Routing in SPUR (informal) (30)	L. J. Lane
9.	Discussion[1] (30)	

[1] See description of items to be discussed at end of the agenda for the General Session.

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General Session

EVALUATING IMPACTS OF SOIL AND WATER CONSERVATION MEASURES

Fred D. Theurer[1]

My topic is evaluating impacts of soil and water conservation measures. The title of this symposium is "Natural Resource Modeling Symposium." Models will be extremely helpful, in some cases even necessary, to evaluate impacts of soil and water conservation measures. Why? Well,

> "The modeling approach has several advantages. First it is efficient. Time frames of many years can be simulated quickly and inexpensively for many locations and management strategies. Second, an unlimited number of management strategies can be considered, whereas in field experiments, only a few can be considered. Third, modeling is a research tool that provides knowledge about agricultural processes and identifies the research that is needed to fill gaps in knowledge."

This passage is familiar to some of you; it is from objective 6 of the Agriculture Research Service Program Plan (ARS 1983). Available facts and examples will show the value and efficacy of operational models to assist a technical action agency.

Important environmental concerns are compatible with USDA program objectives. The examples used here have regional application; but they reflect concepts that, if incorporated properly in operational models, can serve USDA's soil and water conservation programs everywhere.

ONSITE ANALYSIS

Economic justification of USDA's soil and water conservation programs rightfully should begin as onsite analyses, that is, on the farm; but it should not end there.

SCS funded an onsite study to provide analytic support for the 1980 resource appraisal and analysis conducted to comply with the Resources Conservation Act (RCA) of 1977. The study was conducted by Stanford Research Institute (SRI) International, and the final report was submitted to SCS in November 1979. This report provides the focus for my remarks and, possibly, the entire symposium.

The SRI report analyzed four cases:

Case 1 -- no conservation programs,

Case 2 -- current level of conservation programs,

Case 3 -- intensified erosion control, and

Case 4 -- additional drainage of wetlands.

The study was an economic analysis of onsite impacts--benefits and costs--of conservation programs. Benefits were defined as the market value of food and fiber production; costs were defined as capital investments plus operating costs of production. There are, however, other onsite effects, such as possible loss of wildlife habitat. Furthermore, the study reported downstream impacts only as tons of sediment delivered, referring to these as environmental costs.

By the way, erosion control in case 3 was not so intensified as to reduce erosion rates below T values on most of the acres covered in the SRI study.

The report concludes that only case 4--additional drainage of wetlands--usually produces an economic benefit to the farmer. Case 4 also reduced the tons of sediment delivered, although the environmental impacts of additional drainage are obviously not limited to a decrease in sediment delivered! The purpose of this discussion, however, is not the drainage case but the SRI report's findings relative to the three other cases. These findings, in short, are that erosion control is not economically justified by onsite impacts only, and that the economic evaluation of offsite impacts will require further research.

Without that research, we will not be able to develop operational models to evaluate fairly and fully the impacts of conservation practices. This paper's purpose is to explain why that research is needed and to demonstrate, by examples, that offsite impacts can indeed be modeled.

WHEN IS EROSION CONTROL "JUSTIFIED"?

The SRI report concludes that

1. "Erosion control is not generally in the farmers' economic interest"; and

2. From a societal viewpoint, "neither the current level of conservation nor additional erosion control could be justified in terms of economic return over the next 50 years."

In comparing case 2 (current level of conservation) with case 1 (no conservation programs), SRI concluded:

> "Erosion decreases the annual value of food and fiber produced on cropland by about 3% at the end of 50 years . . . in fact, when all food and fiber production is expressed as a cumulative dollar value over 50 years, potential productivity is reduced by only 1.7% as a result of erosion."

[1]Civil Engineer, USDA-SCS, Fort Collins, Colorado.

SRI calculated that the impact of erosion on productivity would be very small despite the many eroding acres because the data used by SRI indicate only a small reduction in yield on severely eroded lands. SCS has identified research on erosion-soil productivity relationships as our No. 1 highest priority research need (SCS 1983).

Data from the SRI report show that, for case 2 (current level of conservation), the farmer gets a return of only 70 cents for his dollar spent while society gets even less--67 cents. For case 3 (intensified erosion control), the farmer receives only 64 cents and society 62 cents. By far, the farmer's expense is the operating costs--91 cents of each dollar spent. But the report did not consider conservation tillage. Would a re-analysis show that conservation tillage lowers operating expenses as well as reduces sheet and rill erosion? SCS wants to know the answer and has identified conservation tillage research as our No. 2 highest priority research need (SCS 1983).

Certain research efforts may seem to affect the importance of research and application of soil and water conservation. Consider the following statement from the SRI report:

> "The USDA data project a 62% increase in yields per acre by the end of 50 years due to improvements in fertilizers, seed varieties, and the like. ... A 3% improvement in yields, achieved over a 50-year period, could replace the loss in yields due to erosion."

In other words, expected yield increases due to other research efforts will more than make up for yield losses attributed to erosion. This conclusion, however, focuses entirely on onsite benefit-cost analysis--not downstream and other offsite impacts.

SRI calculated that, compared to case 1 (no conservation), sediment delivery was reduced by 32 percent for case 2 (current level) and 43 percent for case 3 (intensified control). SRI then concluded:

1. "The current level of conservation is justified only when environmental quality is included in the analysis."
2. "Additional erosion control...cannot be justified on the basis of returns... without including the environmental value of reducing sediment."
3. "A policy decision...depends on the appropriate discount rates and the cost of environmental impacts from sediment as determined by other research efforts."

The report candidly recognizes that erosion control is not likely to be economically justified when focusing on onsite benefit-cost analysis alone. It also recognizes that downstream impacts need to be economically evaluated and will require other research efforts.

Onsite analysis is important; it is the first increment we need to quantify. But analysis of downstream and other environmental impacts generally will be required for socioeconomic justification of our soil and water conservation programs. To do so will require other research efforts. Furthermore, downstream and other environmental impact analysis cannot be limited to tons of sediment alone. SCS has identified the determination of net economic benefits of conservation practices, both onsite and offsite effects, as our No. 5 highest priority research need (SCS 1983).

Economic evaluation of downstream impacts has been restricted mostly to the effects of sediment on water treatment, dredging, and the filling of lakes and reservoirs. I would like to add some more--terrestrial and aquatic resources (Theurer and Bayha 1980). I am going to talk only about aquatic resources, but others will be talking later about both.

Aquatic resources include sport and commercial fisheries in both fresh and salt waters, shellfish, wetlands, and others. Not all aquatic resources can be readily evaluated in monetary terms, but many can. The socioeconomics of certain fishery resources will be discussed after the following report.

In October 1983, the U.S. Fish and Wildlife Service (FWS) submitted a draft final report of the 1982 national fisheries survey to the U.S. Environmental Protection Agency (EPA). This survey is the product of a 5-year effort of the two agencies to assess the biological conditions of the nation's waters. The report is intended for use by water quality management personnel, Federal, State and local decisionmakers and planners, and the general public.

Two findings that are important to us are

1. Without further controls on manmade sources of pollutants, the Nation's fisheries will decline; and
2. Agricultural nonpoint sources appear to be the major contributor to the generally precarious status of the Nation's fisheries.

The report's recommendations focused on the need for more definitive analysis of cause and effect relationships, especially sources of those factors adversely affecting the Nation's waters. In determining research needs and priorities, we cannot ignore this report and its findings.

SOCIOECONOMICS OF FISHERY RESOURCES

Economic values for many fishery resources are available (Loomis and Sorg 1983); others can be developed. By example, this section demonstrates

the economic importance of (1) sport fisheries at the national level; (2) commercial and sport anadromous salmonid fisheries (both salmon and steelhead) in the Pacific Northwest (WA, OR, CA, and ID); and (3) the commercial and sport chinook and steelhead fisheries of the Tucannon River--an upstream watershed in the Columbia River Basin. First, some background information is needed.

Anadromous fish spawn in freshwater, but live their adult lives in the ocean. For example, salmon and steelhead may spawn many miles from the ocean in mountainous streams. The eggs incubate in the stream gravel for several weeks or months before they hatch as fry. The fry reside for a similar period in the gravel interstices until they absorb the yolk sac, when they emerge as juveniles. The juveniles of spring chinook, coho, and steelhead generally remain in the rearing area for 1 to 2 years before going to the ocean as smolts. After a few years (2-5) in the ocean, the adults return to their birthplace as spawners, where the cycle repeats itself. The return of the spawners are called runs.

Salmonids are fish that include salmon and trout.

Salmon is a group of fish that includes many species such as chinook, coho, sockeye, pink, chum, and even the Atlantic salmon. The former are indigenous to the Pacific Northwest. Some have been successfully introduced in the Great Lakes. Atlantic salmon are native to the northeast. All are valuable commercial and sport fishery resources. For example, the National Marine Fisheries Service (NMFS) reports that a Columbia River spring chinook averages 18 pounds. It is a valuable commercially sought fish worth $35 and a much sought-after sport fish worth $143. An escaped spawner is worth $290 because it represents several commercial and sport fish that would not be caught otherwise (MNFS 1982; Meyer et al. 1983). An escaped spawner is a fish that escapes being caught and returns to spawn. Its subsequent progeny is then available to be caught commercially, as sport, or also to return to spawn.

Trout is a group of fish, generally freshwater species, that include such species as brook, brown cutthroat, and rainbow trout. An important exception is the steelhead trout. It is the same species as the rainbow, except it is anadromous. Steelhead are an extremely valuable sport fish. The average adult weight of rainbow is less than 1 pound. NMFS reports that a Columbia River steelhead averages 10 pounds. It has a commercial value of $22 and a sport value of $144. The escaped spawner is worth $244 (NMFS 1982; Meyer et al. 1983).

Striped bass is an anadromous fish species that prefers the warmer waters of the southern California and mid-to-southern eastern coasts. They have been successfully introduced into non-native coastal areas and interior lakes and impoundments. In the Chesapeake Bay area, a native habitat, they are known locally as rockfish. I do not have any monetary values for these fish; but they are considered an important sport fish.

Salmon, steelhead, and striped bass all have one thing in common--significant losses in habitat and dwindling populations. In some areas, their spawning runs have ceased or have critically decreased. The decline in runs is a serious problem in the Pacific Northwest. Alaska has taken steps to protect its salmon resources. Periodically, there is serious concern for the survival of striped bass along native coastal areas such as the Chesapeake Bay.

A 1980 national survey published jointly by the U.S. Fish and Wildlife Service and the U.S. Bureau of Census (1982) produced the following data:

- $17.3 billion was spent in 1980 on sport fishing by 42.1 million anglers over 857.6 million days.
- 2.4 million of these anglers spent 26 million days fishing for salmon and steelhead.
- 4.3 million of these anglers spent 59 million days fishing for striped bass.

Further information on the benefits of water pollution control to recreational fishing is available in the literature (for example, Russel and Vaughan 1982).

The Forest Service (1981) reports that an average of 8.7 million salmon were harvested annually in the Pacific Northwest during the mid-1970's. Sixty-seven percent were commercial harvest. Using 1980 NMFS commercial and sport values, this would amount to almost $434 million worth of fish per year, 83 percent of which is value to sport fishermen. NMFS reports that harvests now are less than half of what they once were prior to major development because of reduced fish populations (NMFS 1982). The Northwest Power Planning Council (NPCC) reports that the number of fish making spawning runs are less than a third (NPPC 1982).

Other reports (NMFS 1982, Chaney and Perry 1976, NPPC 1982) comment on the drastic reduction in salmon and steelhead populations in the Pacific Northwest. They attribute the primary causes to basinwide elimination and degradation of valuable salmon and steelhead habitat, fish-passage losses at mainstem dams, and rapidly growing demands as food.

Bonneville Power Administration has recently raised its rates to fund habitat restoration projects. Proposals are currently being considered to restore spawning habitat in upstream watersheds--in national forests, lands administered by the Bureau of Land Management, and other publicly owned lands. The reasons for starting with streams on government-controlled lands are obvious, but what about private lands?

TUCANNON RIVER

The Tucannon River watershed contains both public and private lands. The river drains about 500 mi^2 of the 260,000 mi^2 Columbia River Basin. It is located in Columbia and Garfield counties in southeastern Washington. The river heads at elevation 6,500 feet in the Blue Mountains of the Umatilla National Forest. It flows into the Snake River, near Starbuck, Washington, at an elevation of 500 feet. The upper third of the watershed is public lands. Here, the river has enough riparian vegetation and clean substrate to serve as satisfactory spawning and rearing habitat. However, returning spawners must first pass through the lower two-thirds of the river, which is on privately owned land used mostly for agriculture. There, the river has lost most of its riparian vegetation. It also receives an influx of fine sediments, predominantly from upland sources, and its banks are unstable (Hecht et al. 1982). These problems are the result of human activities.

The loss of riparian vegetation and the settlement of fines in the gravel interstices combine to reduce the dissolved oxygen in the redds (spawning beds) and to allow metabolic wastes to accumulate. The biologist can predict the effects of dissolved oxygen levels and metabolic wastes on egg mortality. The engineer can predict the effects of riparian vegetation on water temperatures. But we cannot predict the effects of soil and water conservation measures on dissolved oxygen or metabolic wastes, because we do not have the necessary operational models. However, this much is known: The Tucannon River once supported large salmon and steelhead populations, and now the runs are drastically reduced (Kelley 1982). Certainly, a cause-and-effect relationship can be modeled. So far, we have been able to model the thermal regime.

SCS, working with the U.S. Fish and Wildlife Service's Instream Flow and Aquatic Systems Group (IFG), has taken research water temperature and related models and transferred them to operational status (Theurer et al. in prep.). This operational model of instream water temperature was used to study the thermal regime of the entire mainstem of the Tucannon River for May through September during 1980-81, and the normals (Theurer et al. 1983). Four cases were studied:

Case 1 -- existing conditions;

Case 2 -- natural conditions;

Case 3 -- replacing riparian vegetation in part; and

Case 4 -- replacing riparian vegetation total.

Existing conditions are what the name implies; things as they are today. Natural conditions represent what the riparian stream system would be like if the vegetation and stream geometry had not been altered by man; things as they once were. Cases 3 and 4 are riparian vegetation restoration alternatives; things as they might yet be. The difference between case 2--what once was--and case 4--what could be--is that the stream geometry has been altered. This alteration will have a residual effect on the habitat, although not too large if the riparian vegetation is reestablished.

The biologist compared the results of the water temperature predictions with fish population data for juvenile rearing habitat and spawners in the Tucannon River. The analysis shows that correcting the thermal problem alone could increase, by at least 2.5 times, the potential carrying capacity of the river for juvenile rearing habitat and, therefore, the potential return spawners. This increase translates to $1.1 million average annual or to a present value of $6.9 million after all economic factors and discount rates are included. Yet, the cost for total restoration of the riparian vegetation (case 4), including purchasing and planting a 30-foot-wide buffer strip on each side of the stream, is estimated at less than $1.5 million. The net benefit of $5.4 million may be affected by the impact of sediment on the number of fry that will emerge from the gravel. Most of the lower third and part of the middle third does not support successful spawning because of sediment in the gravel (Kelley 1982). An improvement in substrate conditions will increase the total carrying capacity of the Tucannon River. By how much, and its subsequent monetary value, we do not know, because it has not been modeled--yet. This surrogate example, the temperature study of the Tucannon River, indicates that the opportunities for support of USDA's soil and water conservation programs are worth the effort of research and model development to evaluate not only onsite effects but also the offsite benefits and costs as represented by downstream and other environmental impacts.

MODELING REQUIREMENTS

Models are needed to adequately evaluate offsite benefits and likely will be complex and sophisticated. They certainly will require interdisciplinary and interinstitutional efforts for research, model development, and use. Agronomists, soil scientists, engineers, biologists, economists, and other support personnel from various institutions will have to cooperate if useful operational models will be developed and used. Careful coordination will be needed between these efforts and the development of regional and national models of resource assessment and appraisal. The fruits of these efforts--models--can then be used to help

1. Explain USDA programs to both the administration and Congress;
2. Provide direct assistance to farmers;
3. Provide a basis for cost-sharing formulas, especially to quantify societal benefits;

4. Support an additional basis for project justification;

5. Provide an additional basis for project formulation;

6. Prepare environmental impact statements; and

7. Set internal agency priorities.

We in SCS recognize the value of and need for basic and applied research and model development. We recognize an even greater need for operational models that will help us determine the socio-economic factors affecting the adoption of conservation practices--our No. 9 highest priority research need (SCS 1983). Some models will require accelerated water quality research--our No. 11 highest priority research need (SCS 1983). Many of the remaining highest priority, essential, and other important research needs will automatically be required to accomplish the needs already mentioned.

I conclude with the same remark that Joe Haas, our Deputy Chief for Natural Resource Projects, made during the May 1980 American Water Resources Association symposium on Unified River Basin management, that is, a "plea for intensified and premeditated cooperation and coordination at all levels of government and all levels of professional organizations and universities" (Haas 1980). Without such cooperation and coordination, we in USDA will never have the necessary operational tools to totally fulfill our mission.

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SOIL AND WATER CONSERVATION ASSESSMENT MODEL (SAWCAM)

George H. Comer*

BACKGROUND

The Soil Conservation Service (SCS) is the lead Federal agency for developing national policy and administering action programs for the conservation and development of soil, water, and related resources. To carry out this role, the Service collects, analyzes, interprets, and disseminates information concerning the Nation's natural resources. It is essential that SCS provide accurate and complete information developed through sound analytical procedures that are technically valid, repeatable, and amenable to wide usage within the Service. To that end, SCS in cooperation with the Agricultural Research Service (ARS), proposes SAWCAM, a coordinated system of physical-process models linked to socio-economic models and tailored to SCS program needs.

SCS currently uses computer models such as TR-20 (Project Formulation Hydrology), WSP2 (Water Surface Profiles), USLE (Universal Soil Loss Equation), and ECON2 (Economic Floodwater Damage) to evaluate its projects. Because of changes in SCS objectives and technology, these models are inadequate to meet many current program needs. The Agency's conservation objectives resulting from the 1980 RCA appraisal require analytical models and methods we do not now have, for example; (1) models that predict the effectiveness of land treatment measures in reducing upstream flood damage; (2) models or erosion reduction by conservation systems, not limited to homogeneous areas and to no evaluation of off-site effects; (3) better models for streamflow forecasting and for water management to help improve management and irrigation efficiency for greater production; and (4) models of the effects of erosion and other factors on fragile soils and important farmlands and on the productive capacity of our agricultural land. Models and the resulting operational computer programs are the tool the SCS needs. A recent report by the Office of Technolgoy Assessment (OTA, 1982) states that "... models have increased the accuracy of estimates of future events to a level far beyond 'best judgement'... and they have made possible analyses that could not be performed empirically or without computer assistance."

Several studies have examined the need for analytical models within SCS. The reports on soil and water conservation models by Lee (1981) and Margheim et al., (1980), the MITRE report (Gonzalez et al. 1982), the report on model coordination by Okay (1983), and the report on development and coordination of soil and water conservation models by DeCoursey et al. (1983) show how the need for comprehensive and coordinated model development within SCS. Okay's report on model coordination lists 83 models that are needed, yet only 20 have been developed. Three-fourths of the Service's identified needs, therefore, are not met. For may subjects there are several models, but for others there are large gaps in research. The studies all show that SCS has a broad range of modeling needs that can be met only through a coordinated modeling system built upon the research currently being supported by SCS and ARS. Examples of this research are

- Hydraulics and Hydrology model (H&H)--development of improved techniques for flood routing and water surface profiles to replace obsolete technology (SCS 1982).
- Chemicals, Runoff, and Erosion from Agricultural Management Systems. (CREAMS)--a field-scale model for comprehensive evaluation of runoff, erosion, and chemical delivery from homogeneous units (Knisel 1982).
- Simulation of Production and Utilization of Rangelands (SPUR)--CREAMS with added components for rangeland production (Wight 1983).
- Erosion-Productivity Impact Calculator (EPIC)--major emphasis on development of crop growth and nutrient cycling components (Williams et al. 1983).
- Soil-Plant-Air-Water model (SPAW)--soil moisture and plant growth model (Saxton et al. 1981).
- Small Watershed Model (SWAM)--a small water shed model which will incorporate the physical components in CREAMS plus enhancements to deal with effects of erosion, water, and chemicals "downstream" as well as "on the land" (DeCoursey 1982).

Components from all these models, and others, are needed by SCS and will be included in the SAWCAM computer system. Figure 1 illustrates the relationships between these models and the SCS objectives for model use.

The SAWCAM proposal was developed through SCS-ARS discussions organized by the SCS Office of Model Coordination. These discussions showed that broad agency needs could be answered by bringing together technology from many ongoing research efforts into a comprehensive watershed-scale model of conservation assessment.

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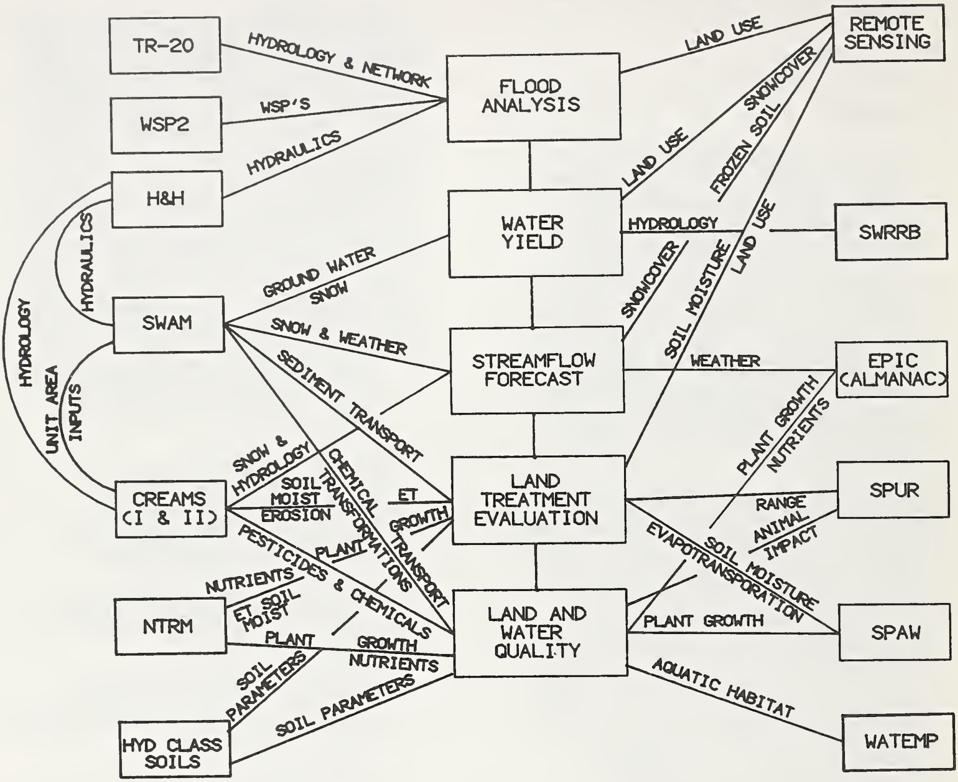

FIGURE 1.--RELATIONSHIPS BETWEEN PHYSICAL PROCESS MODELS AND SAWCAM OBJECTIVES.

Uses of the models range from comprehensive detailed assessment for critical areas to broad assessment for national analyses. Initially, however, it will be a watershed model for use by field offices. Eventually, some components may be used for special, one-time-only analyses.

APPROACH

1. The initial objectives set forth for SAWCAM are broad enough to cover program needs yet narrow enough to be accomplished in a realistic timeframe. The objectives are

- Flood analysis to determine the effects of structural and nonstructural flood-control measures and of land treatments and conservation systems.
- Water yield forecasting for irrigation, multipurpose projects, and snow surveys.
- Streamflow forecasting for snow survey programs and other needs.
- Evaluation of land treatment by evaluation of erosion, sediment, and water supply, onsite or downstream, to determine the effects of SCS's land treatment programs.
- Evaluation of land and water quality, onsite and downstream, to determine the hazard of sedimentation and chemical pollution resulting from various conservation practices.

Figure 2 shows the general relationship between SAWCAM objectives and physical-process models and other models.

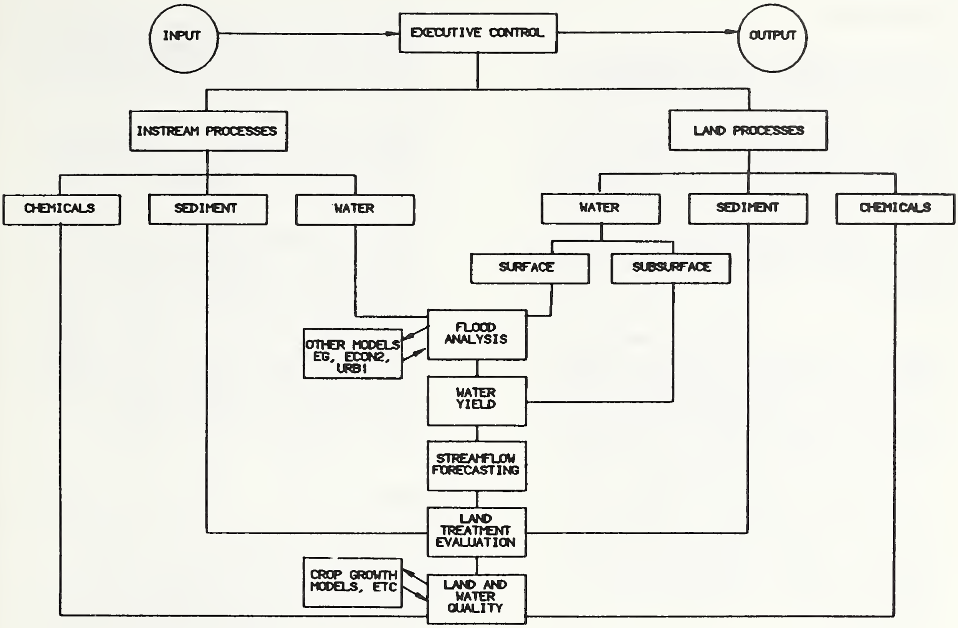

FIGURE 2.--MODEL OBJECTIVES AND PHYSICAL PROCESS RELATIONSHIPS.

2. Identification and evaluation of the available models, development of currently unavailable models, and synthesis of the component models into a coordinated modeling system still remains to be done. These steps will require a partnership of ARS and SCS with a clear division of responsibilities to utilize the strengths of both agencies. This partnership is supported in principle by the OTA report (1982), which recommends "developing comprehensive strategies for building and disseminating water resource models.... "OTA further recommends not directing "...mission agency priorities toward research per se rather than toward coordinated development and utilization of scientific knowledge and related analytical capabilities."

Under this partnership SCS will--

- Establish priorities and requirements and, with ARS, select applicable components and algorithms;
- Work with ARS on simplifying and generalizing of research results; and
- Develop operational computer programs: (i.e., programs tailored to SCS operations).

ARS will--

- Develop and evaluate components;
- Work with SCS on simplifying and generalizing research results; and
- Verify the accuracy of the models.

This division of work draws on the strengths of both agencies while meeting the needs and plans as defined by each agency (ARS, 1983, and SCS, 1983).

Operational computer programs must be computationally efficient, consistent, stable (i.e., maintains accuracy within specified limits and does not require extensive manipulation), and user friendly. The development of operational computer programs will require data bases and data extraction routines; a geographical information system capable of doing analytical overlay analysis; and technically sound, efficient algorithms.

RECOMMENDATIONS

According to a report by the Office of Technology Assessment (1982), "institutional constraints to model use, including lack of information about available models, lack of training in model use and interpretation, lack of communication between decisionmakers and modelers, and lack of general support services, are identified as major impediments to increased model use for water resource analysis." To overcome these impediments for soil and water conservation assessment and to give SCS a comprehensive strategy for effective model development and use, the following recommendations should be implemented:

1. Responsibility for policy coordination should be assigned to the model coordinator under the Deputy Chief for Administration, SCS, and to the National Program Staff of ARS. Technical responsibility and leadership of the operational model development should be assigned to the SCS development team leader, who would report to the Deputy Chief for Technology. This division of SCS leadership is logical to accomplish the task and is in keeping with the Information Resources Management Division's (IRMD) Long-Range Plan (IRMD, SCS, 1983), which was developed with input from SCS personnel in States, national technical centers, and national headquarters.

2. An SCS model development team should work with an ARS team to develop SAWCAM. Initially the project team would consist of a leader, a systems analyst, and an engineer. Other specialists (a soil scientist, a chemist, a biologist, a plant specialist, and so forth) may be added as development progresses. The model development team would be responsible for (1) technical leadership in developing SAWCAM, (2) suggestions for research priorities, (3) the structure and design for the operational computer programs, and (4) working with the model coordinator to establish SCS priorities and maintain schedules. The team's first project should be to work with the SWAM research team in ARS to make SWAM useful for SCS needs.

3. Responsibility for the input and output systems should be assigned to the appropriate SCS staffs. Cartographic and Geographic Information Systems Division should be responsible for providing any geographic modeling; Data Base Technology Branch should be responsible for SCS data bases, access to non-SCS data bases, and extraction procedures; the Snow Survey Data Analysis Group should continue to have the primary responsibility for operational use of their models; and the Engineering Division and User Services Branch should share responsibility for the batch and interactive input routines and the output file processors and report generators. Coordination and schedule monitoring should be handled by the model coordinator.

4. SCS personnel should be designated to work directly with ARS basic and applied research groups. All SCS involvement with model development should be coordinated with the SCS model coordinator.

5. ARS modeling groups should concentrate their efforts on research to improve applications of their models. This may require temporary assignments of individuals from one agency to another. ARS personnel should work jointly with SCS in model testing and simplification. They also should work closely with the SCS model development team in identifying research needs and responding to specific applications of the models. All publications resulting from joint efforts should be coauthored by both agencies.

SUMMARY

SCS must solve a large number of problems in soil and water conservation with limited resources and with limited data inputs in a limited amount of time. Models recently developed by ARS have helped solve some of the problems, but more models are needed. To meet the broad range of modeling needs and to ensure the most efficient use of SCS and ARS resources, a coordinated modeling system--SAWCAM--is needed. Under this system, ARS will concentrate on research to improve or develop the models of interest to both agencies and will provide SCS with technical expertise. SCS will establish priorities, provide data bases (such as soils) and operational expertise, and develop appropriate input/output formats. The two agencies will work together on testing the models, running sensitivity analyses, and simplifying the models, where possible, without significantly reducing their performance. Both ARS and SCS will maintain contact with other agencies, such as the Forest Service and the Economic Research Service, active in model development.

This cooperative effort is in keeping with the recommendations of the OTA report (1982) for interagency cooperation, and with the request made by Joseph Haas, SCS Deputy Chief for Natural Resource Projects for "...cooperation and coordination at all levels of government and all levels of professional organizations and universities..." (1980).

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AN IMPORTANT STEP - TECHNOLOGY TRANSFER

David C. Ralston[1]

What good is technology if it cannot be applied?

What good are working tools if the user doesn't know how to use them?

How well can technology be used if the user doesn't understand the basis for analysis? How can the results be evaluated? Which is the master and which is the servant?

That's what we will be talking about in technology transfer: TRAINING

The SCS geologists, biologists, agronomists, engineers, and other technical support staff specialists are trained in the basic sciences and applied sciences in their disciplines. There have been tremendous changes in these sciences in the last decade and a half since the U.S. public has become concerned about environmental issues. The public has begun to insist that some balance between development, conservation, and preservation be established. The balance is dynamic and will continue to be dynamic.

SCS has trained its employees for the job to be done. Most of this training in the applied field has been a combination of methods, many based upon empirical procedures, to provide working tools. The methods have often been short and simple. Our clientele did not require sophisticated discussions and elaborate justifications. Times changed during the active 1960s. Our clients didn't change their ways, society did. It became necessary for us to consider all of the possible effects of our programs on the community and the environment, even though our clients continued to be individual landowners with specific local problems. Everything became subject to critical examination, even the basis for Ia and the runoff curve number. It is even rumored that T values are subject to scruntiny, so the training also had to change.

In 1972, SCS initiated a course that dealt with the environmental aspects of soil and water conservation. Training included consideration of biological and chemical as well as physical properties. To some, it was like the dawn of a new era. To others, it was like the destruction of an old one.

Recently, SCS initiated a course in analysis of stream mechanics to create an awareness of the state of practice possible in the dynamic analysis of streams. The course has been conducted four times since 1979 by D. B. Simons and several of his associates at Colorado State University. A copy of the course reference sheet from the SCS training handbook is presented at the end of this paper. This course was needed because many SCS engineers and geologists have little training in the currently available quantitative methodologies for analysis of stream transport. In addition, there have been rapid advances in analysis of stream dynamics in the last two decades.

The stream mechanics analysis course provides an overview of the fluvial system from both an engineering and geomorphological reference. Some of the topics covered are hydrology, channel hydraulics, sediment yield and transport, sedimentation, flow resistance (bed form and vegetation), analysis and design of channel static and dynamic equilibrium, and design of channel protection measures. Ecological analysis and design of engineering measures have been added in the last two sessions.

The course has been effective in providing insights into potential application methodologies. SCS has used the technologies described in the course in several situations, from making a geomorphological study of watershed areas to studying channel degradation downstream of proposed reservoir spillway outlets. For some of these analyses, SCS has contracted with specialized consultants. SCS personnel have analyzed channel dynamic equilibrium for existing channels and for proposed designs. Some State office staffs are developing expertise in each analysis. Much more is needed.

In the future, SCS will be making use of computer programs developed in cooperation with ARS for watershed and stream system analysis. In order to properly use these tools, SCS will need training in the basic elements used in the computer programs if these elements are different from or in addition to those generally known. The stream mechanics course will be modified to provide some overview of watershed system computer programs developed with the course emphasis still being on the channel portion. We plan to work with ARS staff involved in computer modeling in conducting the next stream mechanics course. We are looking forward to this cooperative effort. It should provide an opportunity to improve SCS expertise in existing technology and also serve as a vehicle for training in use of computer programs that are available and those that will be developed in the future.

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Let's turn our attention more closely to the purpose of this conference. Many aspects of technology will be discussed at this conference. A variety of expertise will be demonstrated. The objective of efforts during and following this conference is to develop working tools that permit examination of causes and effects in a watershed area.

Who will use the tools? How will they be used? Will the procedures used be understood? Will the results be accepted as valid? There are many more pertinent questions. However, the main question is whether the tools will be used and how well they will be used. Wide use and effective use can be facilitated by developing user-friendly computer programs supported by user's manuals that are concise and well written. The user's manual should not be the technical development reference document. Even with these, the user needs to be trained in the basic processes used by the computer program.

SCS will need to develop a series of training courses or workshops to provide our staff the basic and applied technology. We will need help from ARS in designing and conducting these training sessions. We will likely require several new courses and also significant revision of established courses. Some of the training may be through self teaching with packaged audiovisual media in modular units. Some may be through teleconferencing techniques. Some may be through training of selected staff in State offices.

The training will need to be done at different levels of scope and purpose, varying from orientation for upper management to basic technology for technical specialists. The task is large and the need is essential. The effort spent on developing the tools will be futile without the followthrough in preparing the user. So let's plan together for the future. We will need everyone's help on this.

ENGINEERING - STREAM MECHANICS

COLORADO STATE UNIVERSITY

Subject Code: 8150

Course Title Code: 7195

OBJECTIVES

Upon completion of the course, the participant will be able to:

1. Identify and classify streams according to the hydraulic and bed material parameters.

2. Outline the proper steps and physical parameters needed to analyze and design for stream alterations for any purpose.

3. Prepare design concepts for stream modification features to improve fisheries, maintain or minimize environmental effects created by man-made alterations, and control damage and destruction occurring through natural stream morphology.

LENGTH OF COURSE

Two weeks. Reading assignments prior to the course are expected. Instruction includes problems requiring night work.

WHO MAY ATTEND

Staff engineers and geologists (GS-12 & 13) at the States and NTCs.

CONTENT

The course provides an awareness and understanding of the basic principles of stream hydraulics and the dynamic boundary response. Topics include the dynamics of stream systems from both a hydrologic or hydraulic standpoint and geologic perspective. The principles of both rigid boundary and alluvial (movable bed) channels are presented as well as the effects and analysis of stream morphology and the classification. Also included are the quantitative and qualitative analyses of stream response and stabilization.

OTHER INFORMATION

Nominations are made by the States and NTCs to the National Office where final selections are made. The course is conducted on the campus of Colorado State University and can be taken for college credit.

NATIONAL OFFICE COORDINATED COURSE

Reference: SCS Training Handbook

CHANGES IN AGRICULTURAL RESEARCH

Albert R. Grable[1]

This symposium could not be more timely. As mentioned by several previous speakers, change is in the air and we must be ready to gain advantage. Most of my remarks will be aimed at the Agricultural Research Service (ARS) and research on natural resources but will apply also to the Soil Conservation Service (SCS) and other organizations represented here. In fact, one of the changes I see is a blurring of traditional roles and a merging of interests between agencies. The proposed Soil and Water Conservation Assessment Model (SAWCAM) is an example. The large-scale modeling and applications of systems approaches that will be discussed at this symposium lead one almost automatically into operational planning, economic and environmental assessments, and even the policy arena. Conversely, the world has become so complex that action agencies, policy makers, and others are forced to seek scientific help more and more frequently.

What are the changes occurring around us? They range in scope from the local to the international level. They include reorganizations of agencies and redirections of resources, and a myriad of studies and assessments of how well (or poorly) we are performing. We even have a study on the implications of the ARS strategic plan, including whether or not we are meeting the research needs of SCS. Changes involve transfers of people, reduced personnel ceilings, and closeouts of some research laboratories. They include strategic planning in ARS, targeting in SCS, and the centralizing of all activities in the Economic Research Service (ERS). The whole environment in which we work has changed, and the pace of activities has accelerated.

As one example of the change in the environment in recent years, I was asked to represent ARS on the first interagency workgroup for the Resource Conservation Act (RCA) in December of 1976. John Okay was in the same group. At that time I recommended that ARS respond positively to the request for an assessment of our resource base, and even take the lead if necessary to get it done. Despite my recommendation and urging from Senator Talmadge's staff, little substantive work was done for years. At various times, Dave Farrell, Walter Rawls, Robbie Robinson, Bill Heinemann, Paul Murrman, Earl Burnett, Jack Bond, and I cycled through the RCA workgroup as the ARS representative. The attitude in all the agencies was to give minimal effort; this too shall pass just as all the previous crises. In my opinion, such dawdling would not be tolerated now.

One of the changes of significance to us here is in the relative priority of soil and water conservation. I have never seen these topics higher on the agenda of important national issues during my career. Every year since 1972, and probably before, we submitted budget requests for accelerating research on soil erosion. Every year until recently we were met with a "ho-hum" from decisionmakers. This change in priority is one of the main reasons I feel this symposium is timely--to identify the needs and opportunities in resource modeling. A lot of people are watching us, their expectations are high, and we have a good chance of receiving favorable responses to our ideas.

Another reason this meeting is so timely is the change in science itself. There are two aspects of this change. Don Paarlberg, a former Deputy Secretary of Agriculture, captured one aspect extremely well in a talk he gave to the Joint Council on Food and Agricultural Sciences in July of 1981. He said we already have picked up most of the scientific nuggets from the streambed. Now we need the large and continuing commitments demanded by hard-rock mining. Few universities or research groups have the people or resources to mount and sustain large, long-term efforts. He also said most Ph.D. dissertations in economics at Purdue are not even published anymore because they contain nothing new. A number of large and complicated subjects are evolving and merging such that one discipline or person usually cannot deal with them adequately--subjects such as systems science, crop simulation and yield forecasts, resource modeling, remote sensing, assessments of environmental changes, such as the rising CO_2 levels, weather and climate, and others.

The second aspect of the change in science is the knowledge and tools that are available today for addressing resource conservation. I don't like to think of myself as old, but most of the tools I used as a scientist would be in a museum (if we had one). Using these modern tools, you in this room have built a fantastic knowledge base. Also, as Kenny Renard pointed out so well at our recent systems workshop, you trained yourselves in systems science starting about 20 years ago so you can manipulate that knowledge base with the computers and communications facilities now available. Even so, we have only started to take advantage of the revolution in the physical sciences that occurred 20 years ago. You are going to hear more about remote sensing, artificial intelligence, and smart systems. To one of my vintage, your concepts and research efforts such as Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), Erosion-Productivity Impact Calculator (EPIC), and others are daring and breathtaking in scope. Yet it appears we have only started.

You in this room are the only ones in USDA, maybe anywhere, capable of focusing the power of these new tools and concepts on the complex problems we face in developing improved ways to manage water, soils, and crops for the long term. Managing and participating in multidisciplinary, multilocation projects is not easy, but you have learned to do

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both. In evaluating the systems workshop we held in July, Bill Chace, Associate Regional Administrator for ARS, made the following estimates. If one were to rank, on a scale of 0 to 10, the use of broad-scale systems approaches and modeling in ARS for problem solving, the different program areas would rank as follows:

Natural Resources	9
Crop Production and Protection	5
Animal Production and Protection	2
Post Harvest Technology	1/2
Human Nutrition	0

One of the changes now occurring within ARS is to give more emphasis to systems approaches in future years, even to having a separate objective for the development of integrated systems.

Another change, one we tend to ignore, is time and the aging process. About one-third of the people who attended the ARS Watershed Hydrology Workshop at Fort Collins in 1975 have retired or moved to other organizations. There has been a 100 percent turnover of soil and water staff people at Beltsville in the last 10 years. There's a lot of gray hair and bald heads in this room.

I will spend the remainder of this discussion on the implications of these changes in the hope that it might help during our meeting here. Most of you in recent years have been involved in one way or another in projects cooperative with, sponsored by, or requested by agencies or groups other than your own. The ARS Program Plan says we will give increased priority to developing national programs and meeting the research needs of other agencies. This symposium is a reflection of that priority and intent. I feel the trend toward multiagency, multilocation projects will continue or even accelerate. Both the legislative and executive branches say they want more coordination, cooperation, and joint planning as a condition for their continued support. The ARS has been criticized for placing too much emphasis on local problems. I have discussed the increasing scope and complexity of problems and the need to amass greater resources and more kinds of knowledge. By developing programs like EPIC and CREAMS that cross locations, disciplines, and agencies, we almost by definition have coordination, joint planning, and national programs. We make the most of individual talents and scarce resources, and thereby put out a better product in a shorter time.

Some particular needs that will be addressed here, and I feel the time is ripe, are a merging of resource and crop modeling. Crop production depends upon the quality and quantity of our natural resources. Conversely, plants and their residues are a major factor, often the most important one, for controlling runoff of water and erosion by water and wind. A simple cropping factor in the Universal Soil Loss Equation (USLE) will not suffice anymore for many purposes. Plants don't do well on exposed subsoils devoid of nutrients and too dense for water infiltration or root penetration. What's needed to make those soils productive again? Also, how do we get inputs from weed scientists, entomologists, and others?

Craig Wiegand for years has been pushing the idea that both resource and crop modeling can be aided by using remotely sensed data. This potential must be exploited, and only you can do it. Both EPIC and Simulation of Production and Utilization of Rangelands (SPUR) are designed for bringing another major factor into this mix--economics. The ERS plans to give much greater emphasis in future years to resource economics, and we can help them and vice versa. Merging all these subjects won't be easy. Too often, the experts in the different fields are hundreds of miles away. Travel funds are scarce. We need to figure out ways to overcome such obstacles.

Some scientists see danger in large-scale projects, most notably the potential losses of individual freedom and initiative, and even lack of recognition for their contributions. Such projects often have tight deadlines, require a lot of coordination or direction, and may be imposed from the top. My own feeling is that sessions such as this one will ensure that scientists have a say in setting priorities and determining approaches. In fact, I suspect that the recent cuts in the size of both management and staff ranks are going to require even greater initiative than before from research leaders and individual scientists, if only to write a letter, send a reprint, or pick up the telephone. We on the ARS National Program Staff are not going to be able to visit locations and keep up as well as we used to a few years ago. Some of you do a good job keeping people informed of your perceptions and progress. Others rarely express an opinion. However you do it, make sure you are in the mainstream of the research, an important part of the national program. There is a tremendous pressure on ARS to reduce overhead, duplication, number of locations, and work on local or State problems. In my opinion, being perceived as an "isolated" location or scientist is much more dangerous than being part of a large-scale project.

One problem with large interdisciplinary projects, especially some aspects of modeling, is the matter of individual recognition, especially for those who obtain the basic data. Roles get fuzzy, and who remembers the original source of an idea? Most people at the systems workshop felt this was a major problem, but there were some sharp disagreements. You need to discuss this issue at some point during the symposium. I know of no simple solution to this problem, but conceptually you might start with this thought. Doral Kemper coined the phrase, "The environment we create for each other," for a speech he gave on scientific productivity. There are many ideas one could address in this context, but sharing is central--sharing ideas, energy, and time; working together; taking that extra step to involve others in your projects; keeping each other informed; making sure you recognize the contributions of others.

Some other technical, nitty-gritty problems we need to begin addressing are on the agenda at various places. These problems have to do with the management and uses of data and models. We must do a better job of archiving data and making data sets available to those who need them. We have many valuable, unique data sets in ARS. They were obtained at great cost but are easily lost. In many instances, we need new or more complete data sets for validation of models. Such data must be "geographically referenced", to use Donn DeCoursey's term, so that we can combine and manipulate the different data sets--SCS soils data, topographic data, weather data, vegetation indices and other data from satellites, data on insect migrations from radar, and so forth. Only in this way can we keep track of the data, extract the maximum amount of information, assess changes over long times, and communicate the information to those who need it. From what I read and hear, hardware development already has far outstripped our capacity to manipulate and use the data. Marvin Jensen feels we are way behind other organizations and industry in taking advantage of new techniques for data management. I agree.

A related question is, who is going to maintain a library of models and subroutines, evaluate them, and keep them updated? As Don Baker and Marvin Jensen say, we shouldn't have to keep reinventing the same subroutines over and over. Let's settle on the best subroutine for specific processes and then select the best one for a specific model and use it. Related questions are how to document and reward individual contributions of data, subroutines, and sensitivity analyses; how to ensure a reasonable degree of model validation and balance or congruity of subroutines when the users are clamoring for better tools now, today; or, even, what is validation in the case of model outputs that cover thousands of square miles, project 100 years into the future, or both? One of my co-chairmen, Keith Saxton, feels that modeling today is analogous to statistics back 40 or 50 years ago, in terms of protocols and methodologies. He reminds me you are scientists first and modelers second, but we must keep these considerations in mind to protect both our users and our own credibility.

I want to make one final point about change. An anonymous contributor once said, "Time cuts down all, both great and small." We in ARS research are a legacy of people like Cecil Wadleigh, Louis Glymph, Bill Raney, Carl Carlson, Jess Lunin, Walt Wischmeier, and others too numerous to mention. About 25 percent of the ARS people in this room were trained wholly or in part by ARS, but I don't see as much effort to train people anymore; everyone wants to hire people who can start running now. Admittedly I am biased, but I feel we are making a serious mistake, especially for this group, if we do not increase our efforts to train talented scientists for the future. Dr. Kinney has started a modest training program for engineers, and you will get your share, but it's not enough. Dick Corey, who is on the staff at Wisconsin, pointed it out to me 2 years ago. He said only a few universities can train people with a watershed outlook, specifically those places with ARS watershed research. Dick has a point, I think. Detailing of SCS people and training needs were mentioned in the preceding talk and are interrelated.

To summarize, I urge all of you at this symposium to take advantage of this unique opportunity for meeting new people, exploring new concepts, and determining the future directions of research and development for the United States. Charles F. Kettering once said, "The world hates change, yet it is the only thing that has brought progress." In my experience, those who anticipate change, and take actions accordingly, always profit. The ARS is making some fundamental changes in the way it does business. To a considerable degree, you were the models for those changes through your philosophy and approaches for doing research. You should feel good about that, but Kettering also said, "My interest is in the future because I am going to spend the rest of my life there." Our purpose here is to help shape that future, and the opportunities for doing so have never been greater.

SWRRB, A SIMULATOR FOR WATER RESOURCES IN RURAL BASINS : AN OVERVIEW

J. R. Williams[1] and A. D. Nicks[2]

INTRODUCTION

A model called SWRRB (Simulator for Water Resources in Rural Basins) was developed for simulating hydrologic and related processes in rural basins. The objective in model development was to predict the effect of management decisions on water and sediment yields with reasonable accuracy for ungauged rural basins throughout the United States. To satisfy the objective, the model had to be (a) physically based and use readily available inputs (calibration is not possible on ungauged basins), (b) capable of computing the effects of management changes on outputs, (c) computationally efficient to allow simulation of a variety of management strategies without excessive cost, (d) capable of simulating long periods for use in frequency analyses, and (e) capable of operating on subdivided basins (soils, land use, management, and so forth, make subdivision necessary).

The major processes included in the model are surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage, and sedimentation. The Soil Conservation Service (SCS) curve number technique (6) was selected for use in predicting surface runoff because (a) it is a reliable procedure that has been used for many years in the United States (b) it is computationally efficient; (c) the required inputs are generally available; and (d) it relates runoff to soil type, land use, and management practices. The use of readily available daily rainfall is a particularly important attribute of the curve number technique. Traditionally, the SCS has used an antecedent rainfall index to estimate three antecedent soil moisture conditions (I--dry, II--normal,III--wet). In reality, soil moisture varies continuously and thus curve number has many values instead of only three. Runoff prediction accuracy was increased by using a soil moisture accounting procedure (10) to estimate the curve number for each storm. Although the soil moisture accounting model is superior to the antecedent rainfall method, it does not maintain a water balance and requires calibration with measured runoff data.

The CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (1,11) daily rainfall hydrology model overcame these deficiencies by linking the curve number technique with evapotranspiration and percolation models. Calibration is not necessary because the CREAMS model is more physically based--the soil water balance is related directly to curve number. Although the CREAMS daily rainfall hydrology model is more advanced than earlier curve number models, it was developed for use onfield-size areas (single land use, soil, and management practice) and does not compute water yield (return flow is neglected).

Here the CREAMS daily rainfall hydrology model was modified for application to large, complex, rural basins. The major changes involved were (a) a return flow component was added; (b) the model was expanded to allow simultaneous computations on several subbasins to predict the basin water yield; (c) a reservoir storage component was added for use in determining the effects of farm ponds and other reservoirs on water yield; (d) a weather simulation model (rainfall, solar radiation, and temperature) was added to provide for longer term simulations and more representative weather inputs, both temporally and spatially; (e) a better method was developed for predicting the peak runoff rate; and (f) a simple flood routing component was added. Besides water, SWRRB also simulates sediment yield from rural basins using the Modified Universal Soil Loss Equation (MUSLE) (8) and a sediment routing model.

MODEL DESCRIPTION

The SWRRB model includes three major components: hydrology, weather, and sediment yield. Since SWRRB operates on a daily time step, computer cost for overnight turnaround is only about $0.10 per year of simulation (for a basin with four subbasins) on an AMDAHL 470 computer. The model can be run on a variety of computers since storage requirements are only 105K bytes.

Because of the provision for subdividing basins and because each subbasin can use a different rain gauge, SWRRB is not limited by drainage area. Also, in the vertical direction the model is capable of working with any variation in soil properties--the soil profile is divided into a maximum of 10 layers (the top layer thickness is set at 10 mm and all other layers may have variable thickness).

Descriptions of the SWRRB components and the mathematical relationships used to simulate the processes involved follow. Since several of the SWRRB components are also used in CREAMS (1,11) and EPIC (Erosion-Productivity Impact Calculator) (12), only brief descriptions are given here.

Hydrology

Since the model maintains a continuous water balance, complex basins are subdivided to reflect differences in evapotranspiriation (ET) for various crops, soils, etc. Thus, runoff is predicted separately for each subarea and routed to obtain the total runoff for the basin.

Surface Runoff Volume

Surface runoff is predicted for daily rainfall using the SCS curve number. A depth weighting

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technique is used to express the effect of the soil water distribution on the retention parameter.

The procedure described for simulating surface runoff is similar to the CREAMS runoff model--option one (1,11). The most up-to-date version of the runoff model, a component of EPIC (12), is used in SWRRB. The EPIC/SWRRB surface runoff model accommodates variable soil layer thickness and provides for estimating runoff from frozen soil. If the temperature in the second soil layer is less than 0°C, the curve number is increased by reducing the retention parameter, s, to half its value.

Peak Runoff Rate

Peak runoff rate predictions are based on a modification of the Rational Formula.

The time of concentration can be estimated by adding the surface and channel flow times.

Percolation

The percolation component of SWRRB uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer in the root zone.

The crack-flow model allows percolation of infiltrated rainfall even though the soil water content is less than field capacity. When the soil is dry and cracked, infiltrated rainfall can flow through the cracks of a layer without becoming part of the layer's soil water. However, the portion that does become part of a layer's stored water cannot percolate until the storage exceeds field capacity.

Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer. Water can, however, percolate into the layer.

Since the 1-day time interval is relatively long for routing flow through soils, SWRRB divides the water into 4 mm slugs for routing. This is necessary because the flow rates are dependent upon soil water content which is continuously changing.

Return Flow

Return flow is calculated simultaneously with percolation. Each 4-mm slug is given the opportunity to percolate first, and then the remainder is subjected to the lateral flow function. Thus, lateral flow can occur when the storage in any layer exceeds field capacity after percolation.

Evapotranspiration

The evapotranspiration component of SWRRB is Ritchie's ET model (3). The model computes soil and plant evaporation separately. Actual soil evaporation is computed in two stages. In the first stage, soil evaporation is limited only by the energy available at the surface and, thus, is equal to the potential soil evaporation. Stage two soil evaporation is predicted with a square root function of time.

Plant evaporation is computed as a linear function of LAI (leaf area index) and E_0 (potential evaporation) up to a LAI value of 3. Beyond LAI = 3, plant evaporation is equal to E_0.

Once the total ET is computed for a particular day, it must be distributed properly in the soil layers. A model (9) for simulating plant water uptake is used to estimate the E_p (plant evaporation) distribution.

The distribution of soil evaporation is determined by considering snow cover and soil water content of the top 300 mm of soil. If the water content of the snow cover is equal to or greater than E_S, (soil evaporation) all of the soil evaporation comes from the snow cover. If E_S exceeds the water content of the snow cover, water is removed from the top soil layer if available. If the soil water content is reduced to the 15-bar level and E_S is not satisfied, SWRRB attempts to get water from the second layer, and so forth.

Water Balance for Ponds

This component of SWRRB was designed to account for the effects of farm ponds on water yield. Since pond surface area is required for computing evaporation and seepage, a relationship between surface area and volume is necessary. Data from a large number of stock ponds and small reservoirs in Texas and Oklahoma (5) indicate that surface area can be calculated.

Water Balance for Reservoirs

Although this component was mainly designed to simulate flow through small reservoirs like those constructed on SCS PL566 projects, it can also be used on larger reservoirs. The reservoir water balance component is similar to the pond component except that it allows flow from principal and emergency spillways.

The relationships used to estimate evaporation and seepage from ponds are also applicable to reservoirs. However, the method for estimating is slightly different.

Flood Routing

The SWRRB uses a simple flood routing method to better estimate daily flows at the basin outlet. Without flood routing, the daily basin outflow must be estimated by summing subbasin outflows. For subbasins with long travel times to the basin outlet, the subbasin outflow is lagged and the peak flow rate is attenuated considerably. Thus, flood routing is required to simulate basin outflow realistically, particularly on large complex basins.

Hydrographs must be computed at the subbasin outlets to provide input to the routing model. The peak runoff rate and volume of runoff can be computed for each subbasin, and the hydrograph shape is assumed to be triangular.

To route the hydrograph downstream, a flood routing method that accounts for the variation in travel time with flow depth is needed. Since SWRRB is primarily a long-term water and sediment yield simulator, a high degree of accuracy in predicting hydrographs is not as necessary as for other applications like flood control planning and flood forecasting. Also, SWRRB must operate as efficiently as possible to be useful in water resources planning that requires long-term simulations of numerous management strategies.

Thus, a short-cut flood routing method based on travel time at the peak flow rate and at a low flow rate was developed. The only information the user must supply is the channel top width, bottom width, depth, slope, length, and Manning's n value. These values should represent average channel conditions from the subbasin outlet to the basin outlet. With the given information, SWRRB computes the flow rate and velocity at the full channel depth using Manning's equation. The travel time is computed by dividing channel length by velocity. These calculations are repeated for a depth of 0.1 times the full depth.

The subbasin triangular hydrograph is lagged both in beginning of rise and time to peak, a time equal the travel time at the peak flow rate. The base of the hydrograph is expanded by the difference between the 0.1 q_p travel time and the q_p travel time. Subbasin hydrographs are summed to estimate the hydrograph at the basin outlet.

Snow Melt

The SWRRB snowmelt component is similar to that of the CREAMS model (1). If snow is present, it is melted on days when the maximum temperature exceeds 0°C. Melted snow is treated the same as rainfall for estimating runoff, percolation, and so forth.

Soil Temperature

Daily average soil temperature is simulated at the center of each soil layer for use in runoff and percolation. Simulated air temperature is used as the soil temperature driver.

Weather

The weather variables necessary for driving SWRRB are precipitation, air temperature, and solar radiation. If daily precipitation data are available, they can be input directly to SWRRB. If not, the weather component of the model simulates daily rainfall. Daily temperature and radiation are always simulated. One set of weather variables may be simulated for the entire basin, or they can be simulated for each subbasin. Descriptions of the models used for simulating precipitation, temperature, and solar radiation follow.

Precipitation

The SWRRB precipitation model developed by Nicks (2) is a first-order Markov chain model. Thus the model must be provided as input monthly probabilities of receiving precipitation for two conditions--(a) precipitation occurred on the previous day, and (b) no precipitation on the previous day. Given the initial wet-dry state, the model determines stochastically if precipitation occurs or not. When a precipitation event occurs, the amount is determined by generating from a skewed normal daily precipitation distribution.

If precipitation is to be simulated for each subbasin, the amount generated from the skewed normal distribution is assumed to be the mean for all gauges for the day. The center of the storm is located in a rectangle with boundaries set at a distance of 100 km from the basin's maximum and minimum x and y rain gauge coordinates. Thus, the storm center could be located in the basin or as much as 100 km in any direction from the basin. Each storm center is defined by drawing two random numbers--one for the x scale and one for the y scale. Rainfall at each gauge is computed using an area reduction function. Since only daily rainfall is considered, the duration is unknown. Limited experiments have shown that rainfall duration is exponentially distributed. Therefore, the daily duration is generated from an exponential distribution using the monthly mean duration.

Mean daily rainfall is generated from the skewed normal distribution, and N is the number of subbasins. The amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature. If the average daily air temperature is 0°C or below, the precipitation is snowfall; otherwise it is rainfall.

Temperature

SWRRB generates daily maximum air temperature using the normal distribution equation and weighting factor. A similar equation is used to generate the minimum temperature. The weighting factors are used to provide more deviation in the temperatures when the weather changes and for rainy days.

Solar Radiation

Solar radiation is also generated from the normal distribution. The generated daily solar radiation is constrained between a maximum value and 5 percent of the maximum.

Sediment Yield

Subbasin Yield

Sediment yield is computed for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (8).

Sediment Routing

Ponds and Reservoirs

Inflow sediment yield to ponds and reservoirs is computed with MUSLE also. The initial concentration is input to SWRRB. The inflow concentration can be calculated since sediment and flow are simulated, but the final P/R (ponds and reservoirs) concentration is unknown. It can be computed using the continuity equation.

Channel and Floodplain

The channel and floodplain routing model is composed of two components operating simultaneously (deposition and degradation). The sediment routing function provides a simple mechanism for transporting sediment in a realistic manner. Deposition is greatest for high concentrations of large size sediment flowing for long time periods. Conversely, degradation will usually be insignificant for these conditions. Degradation becomes dominant when relatively clear water flows at high rates for long time periods. Reentrainment of previously deposited particles is greater when the particle size is small.

MODEL TESTS

The Little Washita River watershed located near Chickasha, OK, was selected for model testing. The 538 km^2 watershed is part of an experimental watershed study conducted by the USDA-ARS Water Quality and Watershed Research Laboratory.

The watershed was divided into four areas for model testing purposes. Subbasins 1 and 3 are in the Reddish Prairie Major Land Resource Area (MLRA) but have different soils. Subbasin 2 is in the Cross Timbers MLRA, and subbasin 4 is the large alluvial flood plain. The subbasins make up 29.7, 56.4, 8.5, and 5.4 percent of the total basin area, respectively.

A survey of farm ponds made from maps and aerial photographs shows that 19.5 percent of the basin drains into farm ponds. During 1969-71 19 SCS flood control structures were constructed to control runoff from 17 percent of the basin area. Land-use surveys during 1962-74 indicated that 18 percent of the basin was cropland, 66 percent was rangeland, and 16 percent was nonagricultural.

Simulations were performed for each of four basin conditions: 1) before flood control structures were installed, 2) after structures were installed, 3) assuming no structures for the period after structures were built, and 4) after structures using simulated rainfall for each subbasin.

Table 1 shows the results of the first simulation compared with measured data. Generally, the simulated runoff and sediment compare fairly well with the measured values. It is important for simulation models to produce frequency distributions that are similar to measured frequency distributions. Close agreement between means and standard deviations indicates that the frequency distributions are similar. In table 1 both the mean and standard deviations of measured and simulated runoff compare well.

Table 1.--Comparison of measured and SWRRB simulated water and sediment yield for Little Washita River watershed without structures

Year	Rainfall	Runoff		Sediment yield	
		Measured	Simulated	Measured	Simulated
	----------(mm)----------			-----(t/ha)-------	
1962	763	75	61		
1963	445	27	12		
1964	776	43	68	6.7	4.7
1965	642	32	28	2.9	1.5
1966	487	17	20	0.5	0.9
1967	660	17	27	1.1	1.3
1968	854	35	67	2.7	2.6
1969	702	47	66	5.2	4.4
1970	514	18	27	0.7	3.6
Mean	649	35	42	2.8	2.7
Standard Deviation	142	19	23	2.4	1.6

Mean measured and simulated sediment yield also compare closely, but the simulated standard deviation is considerably smaller than that of the measured sediment yield. With only 7 years, it is difficult to obtain a reliable estimate of the standard deviation. Table 2 contains similar comparisons for the period after structures were installed.

Table 2.--Comparison of measured and SWRRB simulated water and sediment yield for Little Washita River watershed with structures

Year	Rainfall	Runoff		Sediment yield	
		Measured	Simulated	Measured	Simulated
	----------(mm)----------			------(t/ha)------	
1971	780	30	70	2.5	4.4
1972	652	28	84	2.0	5.6
1973	1131	114	151	9.0	7.8
1974	767	64	72	3.6	2.5
1975	929	113	94	7.8	7.1
1976	608	45	19	1.1	0.5
1977	753	51	33	3.8	2.6
1978	669	49	44	4.3	5.6
1979	793	65	54	7.2	3.5
1980	[illegible]	51	69	5.4	8.6
1981	[illegible]	45	51	2.7	2.8
Mean	779	60	67	4.5	4.6
Standard deviation	163	29	35	2.6	2.5

Note the close agreement between means and standard deviations for both runoff and sediment

yield. It is also interesting to compare the information contained in tables 1 and 2 to estimate the effects of structures on water and sediment yield. However, it is almost impossible to estimate structural effects using tables 1 and 2 because of the large difference in rainfall. Structural effectiveness can be estimated, however, by simulating the period after structures were installed, assuming no structures (condition 3). If structures had not been in place, the average annual water and sediment yield during 1971-81 would have been 71 mm and 7.2 t/ha, according to the SWRRB simulation. By comparing these simulation results with those shown in table 2, the structures can be evaluated. From this comparison the structures appear to be quite beneficial--water yield was reduced by only 4 mm per year and sediment yield was reduced by 2.6 t/ha per year. Thus, the structures did not significantly deplete water yield to downstream reservoirs, but they did trap about 36 percent of the sediment that would have been deposited downstream.

The fourth test of the model was the simulation of basin rainfall as well as runoff and sediment yield with structures. Listed in table 3 are the annual amounts of rainfall, runoff, and sediment for ten 11-year simulations. The means of the ten 11-year simulations were compared statistically with observed data. The mean values of rainfall, runoff, and sediment are not significantly different from the observed values at the $t_{.05}$ level.

Table 3.--Comparison of annual rainfall, runoff volume, and sediment load from 10 simulated runs of 11-year length using the SWRRB model and observed data for the periods with reservoirs installed (1971-81), Little Washita River basin

Run	Rainfall	Runoff	Sediment
	----------(mm)--------		(t/ha)
1	677.7	52.27	4.547
2	736.8	72.88	5.485
3	676.2	53.93	3.301
4	702.4	46.76	3.469
5	615.1	27.92	2.093
6	670.7	44.84	3.707
7	687.9	51.33	3.349
8	643.8	49.42	4.163
9	736.9	68.48	5.964
10	674.7	48.90	4.148
Simulated mean	682.22	61.67	4.023
Observed mean	778.63	59.62	4.481
Difference	96.41	7.95	0.458
Critical difference	232.43	32.13	2.620

The simulated average annual rainfall for the period was lower than observed for the 11-year period because rainfall generator parameters were derived from years with less than normal rainfall.

While the tests of the model are not extensive, they do show the performance of the model in simulating the response of large complex basin with mixed land use, numerous control structures such as farm ponds and flood control reservoirs, and varied soils. The tests also indicate that the model performs well when rainfall is generated. This is an important feature that allows for long-term simulations (useful in developing frequency distributions).

SUMMARY AND CONCLUSIONS

The SWRRB model was developed for simulating water and sediment yields from large ungauged rural basins throughout the United States. The major processes included in the model are surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage, and sedimentation. Because of the water and sediment routing components and because each subbasin can use a different rain gauge, SWRRB is not limited by drainage area. Inputs are readily available and the model is computationally efficient.

Tests with data from a 538 km^2 basin in Oklahoma indicate that SWRRB is capable of simulating water and sediment yield realistically. Also, the model's usefulness in evaluating the effects of flood control structures was demonstrated. Thus, SWRRB should provide a versatile and convenient tool for use in planning and designing water resources projects.

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THE EPIC MODEL--AN OVERVIEW

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INTRODUCTION

Accurate estimates of future soil productivity are essential in agricultural decision making and planning from the field scale to the national level. Soil erosion depletes soil productivity, but the relationship between erosion and productivity is not well defined. Until the relationship is adequately developed, selecting management strategies to maximize long-term crop production will be impossible.

The Soil and Water Resources Conservation Act (RCA) of the Congress of the United States requires a report by 1985 to establishe the current status of soil and water resources in the United States. One important aspect of these resources is the effect of erosion on long-term soil productivity. The National Soil Erosion-Soil Productivity Planning Committee documented what is known about the problem, identified what additional knowledge is needed, and outlined a research approach for solving the problem (Williams et al. 1981). One of the most urgent and important needs outlined in the research approach was the development of a mathematical model for simulating erosion, crop production, and related processes. This model will be used to determine the relationship between erosion and productivity for the United States. Thus, a national ARS erosion-productivity modeling team[2] was organized and began developing the model during 1981. The model called EPIC (Erosion-Productivity Impact Calculator) is composed of physically based components for simulating erosion, plant growth, and related processes and economic components for assessing the cost of erosion, determining optimal management strategies, and so forth.

EPIC simulates the physical processes involved simulataneously and realistically using readily available inputs. Commonly used EPIC input data (weather, crop, tillage, and soil parameters) are available from a computer filing system assembled especially for applying EPIC throughout the United States. Since erosion can be a relatively slow process, EPIC is capable of simulating hundreds of years if necessary. EPIC is generally applicable, computationally efficient (operates on a daily time step), and capable of computing the effects of management changes on outputs.

The components of EPIC can be placed into nine major divisions for discussion--hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, plant environment control, and economics. A detailed description of the EPIC components was given by Williams et al. (1983). A brief description of each of the nine components and results of limited testing are presented here.

MODEL DESCRIPTION

Although EPIC is a fairly comprehensive model, it was developed specifically for application to the erosion-productivity problem. Thus, user convenience was an important consideration in designing the model. The EPIC main program and 68 subroutines contain 3500 FORTRAN statements. Since EPIC operates on a daily time step, computer cost for overnight turnaround are only about $0.13 per year of simulation on an AMDAHL 470 computer. The model can be run on a variety of computers since storage requirements are only 300K.

The drainage area considered by EPIC is generally small (~1 ha) because soils and management are assumed to be spatially homogeneous. In the vertical direction, however, the model is capable of working with any variation in soil properties--the soil profile is divided into a maximum of 10 layers (the top layer thickness is set at 10 mm and all other layers may have variable thickness). When erosion occurs, the second layer thickness is reduced by the amount of the eroded thickness, and the top layer properties are adjusted by interpolation (according to how far it moves into the second layer). When the second layer thickness becomes zero, the top layer starts moving into the third layer, and so forth.

Hydrology

Surface Runoff

Surface runoff of daily rainfall is predicted using a procedure similar to the CREAMS runoff model, option one (Knisel 1980, Williams and Nicks 1982). Like the CREAMS model, runoff volume is estimated with a modification of the SCS curve number method (USDA, Soil Conservation Service 1972). There are two differences between the CREAMS and EPIC daily runoff hydrology components: (1) EPIC accommodates variable soil layer thickness and (2) EPIC includes a provision for estimating runoff from frozen soil.

Peak runoff rate and predictions are based on a modification of the rational formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the watershed time of concentration is estimated for each storm as a function of total rainfall using a stochastic technique. The watershed time of concentration is estimated using Manning's formula considering both overland and channel flow.

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Percolation

The percolation component of EPIC uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer in the root zone. Once water percolates below the root zone, it is lost from the watershed (becomes groundwater or appears as return flow in downstream basins). The storage routing technique is based on travel time (a function of hydraulic conductivity) through a soil layer. Flow through a soil layer may be reduced by a saturated lower soil layer.

The crack-flow model allows percolation of infiltrated rainfall even though the soil water content is less than field capacity. When the soil is dry and cracked, infiltrated rainfall can flow through the cracks of a layer without becoming part of the layer's soil water. However, the portion that does become part of a layer's stored water cannot percolate until the storage exceeds field capacity.

Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer. Water can, however, percolate into the layer if storage is available.

Since the 1-day time interval is relatively long for routing flow through soils, EPIC divides the water into 4-mm slugs for routing. This is necessary because the flow rates are dependent upon soil water content which is continuosly changing. Also, by dividing the inflow into 4-mm slugs and routing each slug individually through all layers, the lower layer water content relationship is allowed to function.

Lateral Subsurface Flow

Lateral subsurface flow is calculated simultaneously with percolation. Each 4-mm slug is given the opportunity to percolate first, and then the remainder is subjected to the lateral flow function. Thus, lateral flow can occur when the storage in any layer exceeds field capacity after percolation. Like percolation, lateral flow is simulated with a travel time routing function.

Evapotranspiration

The evapotranspiration component of EPIC is Ritchie's ET model (Ritchie 1972). The model computes potential evaporation as a function of solar radiation, air temperature, and albedo. The albedo is evaluated by considering the soil, crop, and snow cover. The model computes soil and plant evaporation separately. Potential soil evaporation is estimated as a function of potential evaporation and leaf area index (area of plant leaves relative to the soil surface area). The first stage soil evaporation is equal to the potential soil evaporation. Stage two soil evaporation is predicted with a square root function of time. Plant evaporation is estimated as a linear function of potential evaporation and leaf area index.

Snow Melt

The EPIC snow melt component is similar to that of the CREAMS model (Knisel 1980). If snow is present, it is melted on days when the maximum temperature exceeds 0°C using a linear function of temperature. Melted snow is treated the same as rainfall for estimating runoff, percolation, and so forth.

Weather

The weather variables necessary for driving the EPIC model are precipitation, air temperature, soil radiation, and wind. If daily precipitation, air temperature and soil radiation data are available, they can be input directly to EPIC. Rainfall and temperature data are available for many areas of the United States, but solar radiation and wind data are scarce. Even rainfall and temperature data are generally not adequate for the long-term EPIC simulations (50+ years). Thus, EPIC provides options for simulating temperature and radiation, given daily rainfall, or for simulating rainfall as well as temperature and radiation. If wind erosion is to be estimated, daily wind velocity and direction are simulated.

Precipitation

The EPIC precipitation model developed by Nicks (1974) is a first-order Markov chain model. Thus the model must be provided as input monthly probabilities of receiving precipitation if the previous day was dry and monthly probabilities of receiving precipitation if the previous day was wet. Given the wet-dry state, the model determines stochastically if precipitation occurs or not.

When a precipitation event occurs, the amount is determined by generating from a skewed normal daily precipitation distribution. Inputs necessary to describe the skewed normal distribution for each month are the mean, standard deviation, and skew coefficient for daily precipitation. The amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature.

Air Temperature and Solar Radiation

The temperature-radiation model developed by Richardson (1981) was selected for use in EPIC because it simulates temperature and radiation that exhibit proper correlation between one another and rainfall. The residuals of daily maximum and minimum temperature and solar radiation are generated from a multivariate normal distribution. Details of the multivariate generation model were described by Richardson (1981). The dependence structure of daily maximum temperature, minimum temperature, and solar radiation was described by Richardson (1982a).

Wind

The wind simulation model was developed by Richardson (1982b) for use in simulating wind erosion with EPIC. The two wind variables considered are average daily velocity and daily direction. Average daily wind velocity is generated from a two-parameter gamma distribution. Wind direction expressed as radians from north in a clockwise direction is generated from an empirical distribution specific for each location.

Erosion

Water

The water erosion component of EPIC uses a modification of the USLE (Wischmeier and Smith 1978) developed by Onstad and Foster (1975). The Onstad-Foster equation's energy factor is composed of both rainfall and runoff variables. In contrast, the USLE energy factor contains only rainfall variables.

The hydrology model supplies estimates of runoff volume and peak runoff rate. To estimate the daily rainfall energy in the absence of time-distributed rainfall, it is assumed that the rainfall rate is exponentially distributed. This allows for simple substitution of rainfall rates into the USLE equation for estimating rainfall energy. The fraction of rainfall that occurs during 0.5 h is simulated stochastically.

The crop management factor is evaluated with a function of above ground biomass, crop residue on the surface, and the minimum factor for the crop. Other factors of the erosion equation are evaluated as described by Wischmeier and Smith (1978).

Wind

The Manhattan, KS, wind erosion equation (Woodruff and Siddoway 1965) was modified by Cole et al. (1982) for use in the EPIC model. The original equation computes average annual wind erosion as a function of soil erodibility, a climatic factor, soil ridge roughness, field length along the prevailing wind direction, and vegetative cover. The main modification of the model was converting from annual to daily predictions to interface with EPIC.

Two of the variables, the soil erodibility factor for wind erosion and the climatic factor, remain constant for each day of a year. The other variables, however, are subject to change from day to day. The ridge roughness is a function of a ridge height and ridge interval. Field length along the prevailing wind direction is calculated by considering the field dimensions and orientation and the wind direction. The vegetative cover equivalent factor is simulated daily as a function of standing live biomass, standing dead residue, and flat crop residue. Daily wind energy is estimated as a nonlinear function of daily wind velocity.

Nutrients

Nitrogen

The amount of NO_3-N in runoff is estimated by considering the top soil layer (10-mm thickness) only. The decrease in NO_3-N concentration caused by water flowing through a soil layer can be simulated satisfactorily using an exponential function. The average concentration for a day can be obtained by integrating the exponential function to give NO_3-N yield and dividing by volume of water leaving the layer (runoff, lateral flow, and percolation). Amounts of NO_3-N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water and the average concentration.

Leaching and lateral subsurface flow in lower layers are treated with the same approach used in the upper layer except surface runoff is not considered.

When water is evaporated from the soil, NO_3-N is moved upward into the top soil layer by mass flow. Thus, the total NO_3-N moved upward into the top layer by evaporation is the product of soil evaporation and NO_3-N concentration of each layer to a maximum depth of 300 mm.

A loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N loss. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment, yield, and the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that of the soil. A two parameter logarithmic function of sediment concentration is used to estimate enrichment ratios for each event.

Denitrification, one of the microbial processes, is a function of temperature and water content. Denitrification is only allowed to occur when the soil water content is 90 percent of saturation or greater. The denitrification rate is estimated using an exponential function involving temperature, organic carbon, and NO_3-N.

The N mineralization model is a modification of the PAPRAN mineralization model (Seligman and Van Keulen 1981). The model considers two sources of mineralization: fresh organic N associated with crop residue and microbial biomass, and the stable organic N associated with the soil humus pool. The mineralization rate for fresh organic N is governed by C:N and C:P ratios, soil water, temperature, and the stage of residue decomposition. Mineralization from the stable organic N pool is estimated as a function of organic N weight, soil water, and temperature.

Like mineralization, the immobiliztion model is a modification of the PAPRAN model. Immobilization is a very important process in EPIC because it determines the residue decomposition rate, and residue decomposition has an important effect on

erosion. The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms. Immobilization may be limited by N or P availability.

Crop use of N is estimated using a supply and demand approach. The daily crop N demand is estimated as the product of biomass growth and optimal N concentration in the plant. Optimal crop N concentration is a function of growth stage of the crop. Soil supply of N is assumed to be limited by mass flow of NO_3-N to the roots. Actual N uptake is the minimum of supply and demand.

Fixation of N is an important process for legumes. EPIC estimates fixation by adding N in an attempt to prevent N stress that constrains plant growth. Plant growth is limited by the minimum of four factors (N, P, water, and temperature) each day. If N is the active constraint, enough N (a maximum of 2 kg ha^{-1} d^{-1}) is added to the plant to make the N stress factor equal the next most constraining factor if possible. The amount of N added is attributed to fixation.

To estimate the N contribution from rainfall, EPIC uses an average rainfall N concentration for a location for all storms. The amount of N in rainfall is estimated as the product of rainfall amount and concentration.

Phosphorus

The EPIC approach to estimating soluble P loss in surface runoff is based on the concept of partitioning pesticides in the solution and sediment phases as described by Leonard and Wauchope (Knisel 1980). Because P is mostly associated with the sediment phase, the soluble P runoff is predicted using labile P concentration in the top soil layer, runoff volume, and a partitioning factor.

Sediment transport of P is simulated with a loading function as described in organic N transport. The loading function estimates the daily sediment phase P loss in runoff based on P concentration in the top soil layer, sediment yield, and the enrichment ratio.

The P mineralization model developed by Jones et al. (1982) is similar in structure to the N mineralization model. Mineralization from the fresh organic P pool is governed by C:N and C:P ratios, soil water, temperature, and the stage of residue decomposition. Mineralization from the stable organic P pool associated with humus is estimated as a function of organic P weight, labile P concentration, soil water, and temperature.

The P immobilization model also developed by Jones et al. (1982) is similar in structure to the N immobilization model. The daily amount of immobilization is computed by subtracting the amount of P contained in the crop residue from the amount assimilated by the microorganisms.

The mineral P model was developed by Jones et al. (1982). Mineral P is transferred among three pools: labile, active mineral, and stable mineral. When P fertilizer is applied, it is labile (available for plant use). However, it may be quickly transferred to the active mineral pool. Simultaneously, P flows from the active mineral pool back to the labile pool (usually at a much slower rate). Flow between the labile and active mineral pools is governed by temperature, soil water, and P sorption coefficient, and the amount of material in each pool. The P sorption coefficient is a function of chemical and physical soil properties. Flow between the active and stable mineral P pools is governed by the concentration of P in each pool and the P sorption coefficient.

Crop use of P is estimated with the supply and demand approach described in the N model. However, the P supply is predicted using an equation based on soil water, plant demand, a labile P factor, and root weight.

Soil Temperature

Daily average soil temperature is simulated at the center of each soil layer for use in nutrient cycling and hydrology. The temperature of the soil surface is estimated using daily maximum and minimum air temperature, solar radiation, and albedo for the day of interest plus the 4 days immediately preceding. Soil temperature is predicted for each layer using a function of damping depth, surface temperature, mean annual air temperature, and the amplitude of daily mean temperature. Damping depth is dependent upon bulk density and soil water.

Crop Growth Model

A single model is used in EPIC for simulating all the crops considered (corn, grain sorghum, wheat, barley, oats, sunflowers, soybeans, alfalfa, cotton, peanuts, and grasses). Of course, each crop has unique values for the model parameters. Energy interception is estimated with an equation based on solar radiation, daylight hours, and the crop's leaf area index. The potential increase in biomass for a day can be estimated by multiplying the amount of intercepted energy times a crop parameter for converting energy to biomass. The leaf area index, a function of biomass, is simulated with equations dependent upon the maximum leaf area index for the crop, the above-ground biomass, and a crop parameter that initiates leaf area index decline.

The daily fraction of the potential increase in biomass partitioned to yield is estimated as a function of accumulated heat units and the ratio of total biomass to crop yield under favorable growing conditions. Since most of the accumulating biomass is partitioned to yield late in the growing season, late season stresses may reduce yields more than early season stresses. Root growth and sloughing are simulated using a linear function of biomass and heat units.

The potential biomass is adjusted daily if one of the plant stress factors is less than 1.0 using the product of the minimum stress factor and the potential biomass. The water stress factor is computed by considering supply and demand (the ratio of plant accessible water to potential plant evaporation). Roots are allowed to compensate for water deficits in certain layers by using more water in layers with adequate supplies.

The temperature stress factor is computed with a function dependent upon the daily average temperature, the optimal temperature, and the base temperature for the crop.

The N and P stress factors are based on the ratio of accumulated plant N and P to the optimal values. The stress factors vary nonlinearly from 1.0 at optimal N and P levels to 0 when N or P is half the optimal level.

Root growth in a layer is affected by soil water, soil texture, bulk density, temperature, aeration, and aluminum toxicity. Potential root growth is a function of soil water in a layer. It is then reduced with a stress factor which is the minimum of stresses due to soil texture and bulk density, temperature, aeration, and aluminum toxicity. The soil texture-bulk density relationship was developed by Jones (1983). The aeration factor is based on percent air-filled porosity. The temperature factor is based on soil temperature and crop-specific temperature response curves. The aluminium toxicity factor is based on percent aluminum saturation and a crop-specific aluminum tolerance relationship.

Tillage

The EPIC tillage component was designed to mix nutrients and crop residue with a plow depth, simulate the change in bulk density, and convert standing residue to flat residue. Each tillage operation is assigned a mixing efficiency (0-1). Other functions of the tillage component include simulating row height and surface roughness.

There are three means of harvest in the EPIC model: (1) traditional harvest that removes seed, fiber, and so forth (multiple harvests are allowed for crops like cotton); (2) hay harvest (may occur on any date the user specifies); and (3) no harvest (green manure crops, and so forth). When hay is harvested, the yield is computed as a function of mowing height and crop height. Tillage operations convert standing residue to flat residue using an exponential function of tillage depth and mixing efficiency. When a tillage operation is performed, a fraction of the material (equal the mixing efficiency) is mixed uniformly within the plow depth. Also, the bulk density is reduced as a function of the mixing efficiency, the bulk density before tillage, and the undisturbed bulk density. After tillage, the bulk density returns to the undisturbed value at a rate dependent upon infiltration, tillage depth, and soil texture.

Plant Environment Control

The plant environment control component provides mechanisms for applying irrigation water, fertilizer, lime, and pesticide or for simulating a drainage system.

Drainage

Underground drainage systems are treated as a modification to the natural lateral subsurface flow of the area. Simulation of a drainage system is accomplished by simply indicating which soil layer contains the drainage system. EPIC assigns a short travel time of 1 day to that layer. Since travel time depends upon the soil properties and the drain spacing, the drainage travel time may require adjustment for certain applications.

Irrigation

The EPIC user has the option to simulate dryland or irrigated agricultural areas. If irrigation is indicated, he must also specify the runoff ratio (volume of water leaving the field/volume applied), a plant water stress level to start irrigation, and whether water is applied by sprinkler or down the furrows. When the user-specified stress level is reached, enough water is applied to bring the root zone up to field capacity plus enough to satisfy the amount lost in runoff.

Fertilization

EPIC provides two options for applying fertilizer. With the first option, the user specifies dates, rates, and depths of application of N and P. The second option is more automated--the only input required is a plant stress parameter. At the start of the simulation, EPIC estimates the annual N fertilizer rate based on potential fertilizer uptake for the crop at the specified location. At planting time, 75 percent of the estimated rate is applied. After 20 days from planting, an additional application will occur if the N stress factor is the active crop growth constraint and if it is less than the user-specified stress level for fertilizer application. More N fertilizer may be applied 20 days after each application until the crop has reached 50 percent maturity. The N fertilization rate at each of these top dressings is half of the estimated annual rate. The annual rate is reestimated after each year by averaging all previous years' rates. Also at planting time enough P fertilizer is applied to bring the labile P concentration in the plow layer up to the concentration level at the start of the simulation.

Lime

EPIC simulates the use of lime to neutralize toxic levels of aluminum in the plow layer. Two sources of acidity are considered. KCl-extractable aluminum in the plow layer and the acidity associated with addition of ammonia-based fertilizers. The lime requirement due to KCl-extractable aluminum is estimated

according to Kamprath (1970). All fertilizer N is assumed to be urea, ammonium nitrate, or anhydrous ammonium, all of which produce similar acidity when applied to the soil. When the sum of acidity due to extractable aluminum and fertilizer N sum to 4 tons lime/ha, the required amount of lime is added and incorporated into the plow layer.

Pesticides

The three pests considered in EPIC are insects, weeds, and plant diseases. The effects of all three pests are expressed in the EPIC pest factor. Crop yields are adjusted by multiplying the daily simulated yield by the pest factor. The pest factor ranges from 0 to 1--1 means no pest damage and 0 means total crop destruction by pests. Pesticides are applied on user-specified dates as part of the EPIC tillage operations.

MODEL TESTS

EPIC simulations have been performed on 150 test sites in the continental United States and 13 in Hawaii. Crop yield results of the simulations for 12 of the test sites from the continental United States are shown in table 1. These 12 test sites were carefully conducted experiments that provided measured inputs for weather, management practices, and fertilizer rates. Table 1 contains both measured and simulated means and standard deviations of crop yields. It is important that simulation models produce frequency distributions that are similar to those of measured data. Close agreement between simulated and measured means and standard deviations indicates that the frequency distributions are similar. Generally, the simulated results compare closely with the measured values, although it is difficult to obtain accurate estimates of standard deviations with such short periods of record.

Table 2 shows results from 13 test sites in Hawaii. Data from each site included corn yield for 1 growing season, weather information, management practices, and fertilizer rates. Although it is not possible to estimate means and standard deviations with only one year's data, these sites provide an excellent test of EPIC's response to N fertilizer. The simulated yields generally agree fairly well with measured yields, although there is some discrepancy for some sites at low levels of N fertilizer. Overall, the test results appear satisfactory, particularly since the crop and all other model parameters remained constant for all tests shown in tables 1 and 2.

CONCLUSIONS

The EPIC model is operational and has produced reasonable results under a variety of climatic conditions, soil characteristics, and management practices.

More extensive testing is planned for EPIC. Although some components of the model like hydrology and erosion are based on accepted technology, other components will require rigorous testing for validation. The two components that will need testing most are crop growth and nutrients. This is true because these are newly developed and because they are extremely important to the success of the EPIC model.

EPIC has many potential uses beyond the RCA analysis, including (1) conservation policy studies, (2) program planning and evaluation, (3) project level planning and design, and (4) as a research tool.

Table 1.--Comparisons of simulated and measured crop yields for sites in the continental United States

State	County	Yr	Crop	Yield (kg/ha) Meas.	Yield (kg/ha) Sim.	Std. dev. Meas.	Std. dev. Sim.
IA	Monona	5	Corn	6996	7653	1110	1035
IA	Monona	5	Oats	1755	2225	774	1000
IA	Monona	10	Corn	6162	7325	1908	1895
IA	Ringold	7	Corn	7270	7235	1702	798
IA	Ringold	7	Soybeans	1910	2065	284	531
IA	Ringold	10	Corn	6593	7095	1296	1075
IA	Story	5	Corn	6664	7580	815	790
IA	Story	5	Corn	6575	7265	922	1215
IA	Story	5	Corn	6077	7250	1279	1210
IA	Story	4	Corn	7033	7205	1010	1175
MO	Boone	10	Corn	7833	7632	2077	1635
OH	Coshocton	3	Corn	8399	7460	2665	2020

Table 2.--Comparison of measured and predicted corn yields for irrigated plots in Hawaii with various N fertilizer rates

Plot name	Measured/predicted yield (kg/ha) N fertilizer rate (kg/ha)					
	0	29	70	108	144	186
KALB B21	2655	4971	6441	7059	7622	8169
	1848	3244	4558	5439	6455	7527
IOLE E11	3202	5079	6638	7439	6957	7176
	3102	4100	5200	6365	7287	8404
UIKE U19	3723	3268	4076	5580	6409	6600
	3115	3949	5196	6681	7590	7919
KUK A21	3616	6499	6357	6561	7174	6962
	3386	4294	5603	6614	7436	7634
KUK A22	1733	3357	4190	4457	4673	4549
	3672	4420	4929	5186	5245	5296
KUK C11	4005	7358	7257	8269	8161	8768
	3679	4460	5747	6818	7832	8825
KUK D11	3715	6293	7663	8254	8291	8471
	3976	4735	5802	6737	7652	8551
KUK D12	2867	5546	6889	7766	7892	8828
	3118	4207	5396	6654	7763	8870
MOL A10	6628	7953	9266	9928	9390	10462
	6451	7712	8990	10148	10704	10918
MOL A11	2162	3833	4971	5343	5443	5537
	2978	3670	4794	5855	6545	7599
	N fertilizer rate (kg/ha)					
	0	32	83	129	174	225
HAL B22	891	2292	5339	6863	7815	8629
	2242	3610	4664	6003	7223	8320
KUK C12	3824	7249	8221	8984	9213	9262
	3428	4281	6200	7426	8569	9651
	N fertilizer rate (kg/ha)					
	0	27	63	95	127	163
MOL B10	2539	4983	6087	6985	8546	8773
	2214	2945	3835	4718	5606	6457

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SOME THOUGHTS ON THE FUTURE OF EPIC FROM A SOIL SURVEY VIEWPOINT

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At this juncture all indications are that the EPIC model will be used by the SCS to supply erosion predictions for the next Resource Conservation Act cycle.

The results of the validation run on 10 percent of the total soil groups have been reviewed by SCS staff knowledgeable about these specific groups. Based on this review, changes are being made in the model. One change is that the curve number (and hence the runoff) is adjusted for slope. Another change is that the K of USLE and the I of the wind erosion equation are computed from soil composition as the soil is progressively truncated. The validation runs will be repeated with the changes that have been made in the model, based on the first run. Validation run results will be confirmed by SCS personnel conversant with the soil groups. If the validation runs are confirmed by these people, production runs will be initiated.

After the production runs, attention will turn increasingly to a more sophisticated EPIC model referred to as ALMANAC. The following personal suggestions, reflecting my background in the soil survey, pertain to the development and application of ALMANAC.

First suggestion.--Use knowledgeable SCS personnel to select physical field points for model application that would characterize the landscape in a way that is meaningful for erosion concerns. Most of the cropland is mapped in the United States. Further, the SCS has personnel who are very conversant with local conservation practices. These people could select representative points in delineations of map units that, in their judgment, should be critical in planning conservation measures for the map unit. The soil and ground surface configuration (slope, LS, and so forth) for the point could be determined and employed in ALMANAC. The results would not apply to the overall map unit but to the part on which conservation decisions presumably would be made. This may be an economical way to approach the complexity of landscape description.

Second suggestion.--This assumes that ALMANAC will evolve towards description of agricultural watersheds (possible even by marrying with CREAMS). Let us suppose that we have the capability for modeling small watersheds. How than would one describe large areas? One possibility would be through the soil association. (Soil associations have been assigned to some 90 percent of our cropland.) Soil associations are generalizations about the occurrence of soils on landscapes at a scale for cropland that is compatible with fields of most commercial grain and/or large animal farm enterprises. There are 5 to 15 soil associations in a typical soil survey. For a State portion of a Major Land Resource Area, the soil associations among different soil surveys are similar and can be grouped to yield a short list. Typifying field size watersheds would be selected for each of the soil associations on the list for a State portion of a Major Land Resource Area. The number of typifying watersheds selected for each association would depend on the landscape characteristics of the soil association. In some instances, one would suffice, and in others, several would be needed. Our future EPIC model would be run using landscape information for these typifying watersheds. The results could be aggregated for the State portion of a Major Land Resource Area from the proportion that each listed soil association is of that Major Land Resource Area. We could then construct State and regional evaluations by aggregating the State portions of Major Land Resource Areas. Moreover, a catalog of watersheds could be assembled on which our future model has been applied. To predict behavior for a particular farm, the most similar watersheds from the catalog would be used.

Third suggestion.--Make greater use of the map unit and place less emphasis on soil taxonomic units (soil series is the most common). The map unit is the definition of the concept that is actually mapped; all delineations of the map unit should meet this definition. It is in the map unit description, not the taxonomy concept, that we have the information about near surface texture, slope class, and the degree of erosion. It is by the map unit mainly that we organize the information in standard soil survey reports. A strength of the approach to erosion and productivity by Bill Larson and the University of Minnesota group, is that they used the map unit. Composite lists of map units can be made for State portions of Major Land Resource Areas in a manner parallel to that described previously for soil associations. Models can be run on these composite lists of map units and applied to any area from county size up to the whole State portion of the Major Land Resource Area. The composite list of map units need not be long. We did an exercise on 11 State portions of 8 Major Land Resource Areas. We found that a median of only 40 map units encompassed 90 percent of the cropland subject to erosion (Land Capability Classes IIe, IIIe, and IVe).

Fourth suggestion.--This concerns the soil survey program. In general, we do not include soil use as a criterion for ordering soil information. Part of a delineation of a map unit in Ohio, for example, may be in mature hardwoods and the other portion in corn. Infiltration, near-surface bulk density, snow cover, the yearly patterns of water states, soil temperature including frost depth, and so forth, are undoubtedly different between these two uses. Yet, in standard soil survey documentation the two areas are not distinguished. There would seem an argument for an enlarged portion of the soil survey effort being put into the

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collection of use-dependent soil properties and to the development of a soil systematics for ordering the information. Modelers need use-dependent data both as checks and as inputs. Further, modelers need a soil systematics that includes soil use in order to more effectively apply their capability to compute various quantities. For example, the prediction of soil temperature at shallow depth requires information on the cover. To specify the cover requires a definition of the soil use--hence, a soil systematics that includes use.

Fifth suggestion.--ARS and SCS should select a very few soil surveys, perhaps a half a dozen, and concentrate on the collection of the information needed to validate and implement our models. Ideally, they should be surveys that have been or will be digitized, have an applicable Federal Experiment Station, and be in SCS targeted areas. We need concentration of effort and a common link to a specific area of land.

SUMMARY OF METHODOLOGY IN THE CREAMS2 MODEL

R. E. Smith[1] and W. G. Knisel[2]

PREFACE

A national project began in 1978 to develop mathematical models for evaluating non-point-source pollution. The initial effort, funded for 1 year, concentrated on a model for field-size areas since the field is the site where management practices are designed and implemented. The first meeting of scientists was held at Arlington, TX, in February 1978 to plan for the model development. The 6-month time frame within which the scientists had to develop a product necessitated taking readily available components, or those that could be readily modified, for a basic model. With simplifying assumptions and self-imposed limitations, the lead scientists were to develop a somewhat state-of-the-art model that would be usable and useful, primarily to the Soil Conservation Service, to develop management practices for a wide range of climatic and physiographic conditions. It was recognized that in some intermediate time frame a more comprehensive model would be needed to represent the complex real world system.

Through the diligent efforts of all scientists to accomplish their assigned tasks on schedule and the concerted efforts of the lead scientists to assemble the components, the basic model framework was developed on time. This resulted in favorable consideration to continue the project. Model testing and analyses were conducted over the next year, and CREAMS was published in May 1980 (USDA 1980). Also in 1980, a budget increase was received by ARS to further the overall research program in soil, water, and environment.

Following publication of CREAMS, concerted efforts were made by SCS and ARS in technology transfer and application of the model in projects where water quality problems had been identified. Further testing and application resulted in SCS's acceptance in 1982 of CREAMS as a tool to aid in the development of resource management systems. Simultaneously, many other CREAMS model users emerged from other Federal and State agencies, consulting firms, and private industry both nationally and internationally. Despite model limitations, many varied applications of CREAMS were made. Some of the applications were beyond those initially anticipated by the modeling scientists.

Technology transfer was implemented in its true sense of interactions and feedback rather than a "here's-how-to" effort. Interagency personnel assignments (IPA's), were established by ARS and SCS. Feedback through these interactions, along with that from other users, helped identify model deficiencies and limitations that needed improvements. Scientists' respective research programs and their recognition of improved technology consistent with the modeling concepts, along with user response, resulted in a continuing project to make CREAMS more comprehensive in processes considered, more representative of the physical system being modeled, and more streamlined in its input for better user acceptance. Since 1981, the lead scientists have continued in the development of CREAMS2. The basic model structure has been developed, and this paper gives an overview of the model.

INTRODUCTION

CREAMS2 is a computer simulation model for runoff and pollutant transport in and from an agricultural field. Its purpose is to predict the effects of agricultural management practices on non-point or distributed-pollution sources from field size areas. To the limits of available data, it is based on the physics of soil water flow within the soil profile and over the soil surface. Given only daily precipitation data, the empirical but widely used SCS curve number method is used to estimate runoff. In addition to and in conjuction with water movement, the model includes the processes of snowmelt, erosion and sediment transport, nutrient cycling, adsorbed and dissolved chemical transport, soil heat flow, crop growth, and residue decay. A wide variety of agricultural management practices may be simulated, and the model treats their effects on all of the above processes. The management practices considered include crop rotations, all types of tillage operations, irrigation, inorganic fertilizer and animal waste application, grazing, pesticide application, tile drainage, farm pond effects, terracing, and buffer strips.

The model's scope is limited to those areas (1) which can be characterized by a single soil profile regime, (2) whose hydrologic description does not require channel networks of order greater than 2, and (3) within which a single cropping system and single management practice are contained. It is not limited to annual crops but can also treat perennial grass and forest systems, as well as grazed or annually harvested meadows.

CREAMS2 has been constructed for the same purposes as was CREAMS but includes new capabilities, and it is a significantly different and in most respects a more physically based model. The outline below summarizes the major differences between the two models. CREAMS2 is a single integrated model rather than a three model set and uses a set of flag parameters or "switches" that allow selection of those options which the user wishes to include in a given simulation. CREAMS2 provides a choice of four options for hydrologic methodology, depending on the type of rain data available and the hydrologic rigor required in the estimate of runoff and sediment transport dynamics.

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Outline of Major CREAMS2 Changes

	CREAMS	CREAMS2
FEATURE:		
STRUCTURE	3 Sequential Models -Hydrology -Erosion & Sedimentation -Nutrients & Pesticides	1 Integrated Model -Interactive Structure -Optional computations
INPUT/OUTPUT UNITS	Hydrology & Erosion: English units only Chemistry: English output only	Metric or English Input and/or Output
MANAGEMENT PRACTICES	External, by parameter changes.	Efficient specification for cultivation, fertilization, irrigation, drainage, manure application, grazing.
	No feedback between models.	Affect all model components.
COMPONENTS AND PROCESSES:		
HYDROLOGY	2 OPTIONS: Daily Rain Breakpoint Rain	3 OPTIONS: Stochastic Generation of Daily Rainfall Read Daily Rain Read Breakpoint Rainfall Record
Daily Rain	EI estimated by from rainfall.	EI related to rainfall, peak, and monthly record of intensities.
	Peak flow by regression	Peak flow stochastic, related to time of conc.
Breakpoint Rainfall	Estimates Peak and Runoff only.	Full Kinematic Solution
	Independent Infiltration Parameters.	Infiltration Parameters from Soil Parameters.
	Invariant Flow Topography	Alternate Flow Topography for Furrow Control.
Snowmelt	Degree-day estimate	Degree-day plus heat from soil.
	No runoff	Runoff calculated. Frozen soil estimated.
Terrace Impoundments or Ponds	No routing through ponds	Flows routed through ponds.
Soil Water	"Tipping Bucket" storage storage routing	Solves Richards' Equation.
	One soil type No heat flow	Up to 10 soil horizons Calculates soil temp. by heat flux.
	Independent surface evaporation.	Soil evap. linked to flux limit.
EROSION/ SEDIMENTATION	1 Option only: Steady flow profile estimate method	4 Options: 3 for Daily Option: -MUSLE -As in CREAMS, improved. -Quasi-dynamic using triangular rain excess pattern. Fully dynamic with breakpoint Option
	External updates for management changes	Internal updates for management changes
CHEMISTRY		
Solute Transport	Some from surface zone to lower zone	Complete through profile, with variable adsorption.
Pesticides	Surface Zone only	Throughout profile
Nutrient Cycling	Uses air temp. Interstorm time step No N-fixation. Profile lumped.	Uses local soil temp. Daily time step N-fixing by legumes. Calculations by layer. Improved carbon cycle related decay functions
PLANT GROWTH	Fixed by LAI diagram, modified only by soil water stress.	Mechanistic model, driven by radiation and degree-day age. Water, heat and nutrient stresses considered.
METEOROLOGY	T and R are fixed daily means.	T and R are either fixed at record daily means or randomized sympathetic with rain. Allows use of pan data as alternate estimate of potential ET.

Crop or plant growth and surface and soil water flows are simulated by the model in every case. Optional simulations that can be concurrently performed include erosion and sediment transport, pesticide and nutrient transport, nutrient cycling (transformations) for both N and P, irrigation draintile outflow, terraces and terrace outlet channel routing. Either daily net radiation or daily pan evaporation data may be used to estimate daily potential evapotranspiration. For use when measured rainfall sequences are not available, a model is included to generate daily rainfall sequences from climatic parameters, examples of which are provided for various locations around the United States. The model constructs the annual mean daily radiation and temperature values from monthly summaries, and the user may opt to use these or allow the model to generate a random correlated sequence having deviations around these means, which are correlated in turn with the rainfall sequence.

The user can select to provide input data in either metric or English units and obtain a variety of output detail in either metric or English units.

Hydrologic Simulation

Table 1 summarizes the principal differences in the four hydrology options available within CREAMS2. Options 1 through 3 utilize daily rainfall records and enable the additional optional generation of daily rainfall from a monthly averaged set of five, statistical rain-model-generating parameters, rather than requiring input of actual recorded data. Daily values from recorded monthly mean maximum and minimum temperatures and radiation can be used, or daily values generated randomly in harmony with the rainfall record can be used. Each of the first three options employs the SCS curve number procedure to estimate daily runoff. Option 4 is a more physically correct, infiltration model approach and requires rainfall rate pattern data in the form of breakpoint hyetographs.

Option 1 is basically a spatially and temporally lumped parameter method. Option 2 uses a spatially distributed estimation of a time-lumped runoff methodology. Steady flow is assumed. Option 3 estimates a time distribution for runoff pattern so that the surface hydraulic conditions can be treated as time and space distributed. Option 4 is a fully distributed hydrology simulation.

Surface Water Flow.

Options 2 thru 4 take advantage of a significant amount of distributed topographic information, including a variety of field/channel/impoundment networks, plus description of slope profiles and furrow-controlled flow. Options 1 thru 3 utilize variations in estimated time to peak from this information, and option 4 uses the field data directly in surface water dynamics. Infiltration for option 4 uses the Smith and Parlange (1978) equation, with modifications to treat dynamic crusting properties.

Table 1.--CREAMS II comparison of hydrology options

Hydrology	Rain data required	Stochastic rain generator available	Runoff calculation	Peak runoff	Erosion methodology	Sediment particle size distribution simulated
1	Daily	Yes	SCS CN	Estimated from runoff volume	MUSLE (lumped)	No
2	Daily	Yes	SCS CN	Estimated from runoff volume	EROS 2 (distributed in space using steady flow)	Yes
3	Daily	Yes	SCS CN	Estimated from runoff volume	distributed in using steady flow)	Yes
4	Breakpoint (Pluviograph)	No	Infiltration model	Taken from hydrograph	Unsteady, spatially distributed	Yes

Subsurface Water Flow

CREAMS2 can utilize a large amount of information on the soil characteristics in its simulation, including capillary characteristic curves, as well as organic and nutrient data. Soils can be characterized as composed of as many as 10 separate horizons (fig. 1). Tables are provided to help the user estimate the unsaturated hydraulic parameters on the basis of texture class (Rawls et al. 1982). Infiltration parameters are obtained within the program from this data. Soil water is redistributed between storms by solution of a θ-based form of Richards' equation, using an internally optimized time step to minimize computations. This solution is linked with the draintile simulation (if so chosen by the user), and to a potential-based distribution of root water extraction. During a storm, infiltrating water brings various solutes and heat, and this transport is calculated simultaneously with water flow by using convection and diffusion equations for adsorptive materials.

Erosion and Sediment Transport

Each hydrologic option has an appropriate level of erosion and sediment transport equations linked to it for optional use (table 1). Option 1 employs MUSLE as in the EPIC model (Williams et al. 1982). Options 2 thru 4 employ spatially distributed continuity equations as a basis, and option 4 in addition considers the time distribution of these processes. Soil conditions--such as crusting, loosening by cultivation--are considered explicitly by program modification of erosion parameters such as soil loss ratios in field surface flow and critical shear stresses for concentrated flow erosion (Foster et al. 1983). Erosional changes in flow channels are likewise reflected in changes in hydrologic response. Transported sediment carries with it adsorbed chemicals

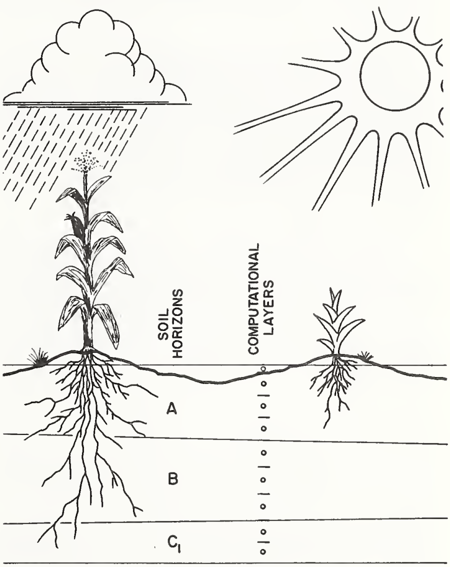

Figure 1.—User specified soil horizons are subdivided by the model into computational layers, favoring smaller increments toward the soil surface.

which are part of the pollution load calculations.

BIOLOGICAL AND CHEMICAL DYNAMICS

Nutrient cycling and plant growth are functions of temperature and soil water. CREAMS2 uses a daily time step for these processes. Although temperature and soil water affect pesticide degradation, these relationships have not been defined, and CREAMS2 uses an interstorm time interval for estimating degradation.

Soil Nutrient Transformations

Soil N and P cycles are followed with daily calculations of dynamics on a layer by layer basis, using a model patterned after Parton et al. (1982). Fertilizers, rainfall, and manure applications constitute the mass inputs to the system, and soil temperature, nutrient contents, and water contents are the major variables considered. N is lost as NH_3 and N_2 and by runoff, erosion, and seepage transport. N and P uptake by plants and removal by harvest are also simulated. Organic carbon is also accounted for, and C:N:P ratios are used in estimating transformations during decay.

Pesticides

Depending on specified method of application, pesticides are assigned to a soil or plant surface origin and then transported and decayed with all water flow processes. Leaching of applied pesticide from residue and plants into both runoff and infiltration is simulated. Pesticide properties such as adsorption, solubility, and decay rate are considered.

Plant Growth

The plant growth model accounts for both perennial and annual plants. Also, it considers the plant in a mechanistic manner to be responsive to water, temperature, and nutrients and to grow and decay with a degree-day "clock," based on genetic potential. The model is described in more detail elsewhere in this symposium proceedings.

Stimulating Field Management Operations

The method of specifying management operations considers tillage, fertilization, pesticide application, and irrigation operations; and it draws details from user supplied lists of crops, fertilizers, manure types, pesticides, and field operations. This minimizes the repetition of input. Specified field operation dates are delayed when the field is unsuitably wet; and when performed, field operations may include soil surface modifications such as mixing, shaping, roughening, and chopping or incorporation of plant material. Pesticides and fertilizers may be applied with irrigation water, and fertilizers and manures may be surface applied, incorporated into the soil to a given depth, or injected to a given depth. Pesticides may be aerially applied under all field conditions.

SUMMARY

This is only a general overview of the model features and methodology, since space does not permit more detail. CREAMS2 represents a significant and comprehensive improvement over the first CREAMS model in (1) its ability to represent the physical, dynamic interactions involved in agricultural water-borne pollutants and (2) its ability to represent a greater variety of management treatments with a wider range of model complexity options.

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CREAMS2 MODEL: SCS RESPONSE

James N. Krider[1]

I will open my remarks with laudatory comments--SCS to ARS--for the technology transfer job that has been done and continues to be done. Without your devotion, ARS, to helping SCS with model development, we would still be at the starting block. For the most part, SCS doesn't have the talent or time and resources for a major model development effort. On behalf of my colleagues, thank you for your time, for your patience, and for your hard work.

I'm not going to attempt a point-by-point review of Dr. Smith's presentation. I believe I can be more productive by surfacing, in an overview fashion, concerns, areas of suggested improvements, and actions that need to be taken. The actions that I mention will be from an SCS perspective--but, there is no way that SCS can successfully accomplish most of what remains to be done without continued ARS assistance.

I've chosen to focus my presentation on the question: "What's the ultimate goal for the CREAMS water quality model as perceived by SCS?"

There are probably as many answers to that question as there are people attending this conference. My blush on that question is rather a broad brush type, but really gets at where we, the user, need to go.

The CREAMS water quality model should be a tool that can be used by SCS field office/conservation district personnel to assist land managers in making the best resource management decisions. We are presently not too close to such an objective--most of the use has been by people at the higher levels, our four national technical centers (NTC's) and state offices.

A footnote here: ARS has been interfacing with a small group of SCS people who have an acumen for the task ahead, and due to the size of the group, the yield hasn't been large as yet. But, it's growing arithmetically and, in fact, gaining momentum toward growing geometrically.

Granted, we're not very close to use at the field office or conservation district level, but we'd be much less than bright if we didn't realize that it is a matter of time before micros with the necessary power will be used at the lowest echelons within SCS. Our sister agency, the Forest Service, is moving toward this sort of setup, and can we not believe that farmers will be using micros and other sophisticated hardware in the future?

Our thrust will need to be toward developing an interactive model that most anyone with average intelligence and good understanding of soil and water will be able to load. This means that the data for loading will have to be readily available at the field office level. We in SCS will not be able to collect a lot of data, therefore, the model will have to be easy to use. It'll have to be basically different from the research models that are being developed for research purposes.

This puts a responsibility on managers--they will have to weed out the models that will not have a payback, and if they're too complicated, there will be no payback. The technical community has a big responsibility here, too. Without it's strong guidance, the managers will not make the best decisions.

How do we proceed? Well, the precedent is set. CREAMS reached its present operational state for SCS use through a cooperative program between ARS and SCS. This cooperative program bore fruit for SCS because SCS made a commitment to the model's development: it committed by assigning an SCS professional to work on a daily basis with ARS scientists in a technology transfer effort. ARS made a commitment to the development; SCS made a commitment to the development. The commitments were to the mutual benefit of both.

SCS needs a continuous input through a person who has the specific assignment to help when SCS field people run into problems. Such a person can also work daily with ARS scientists on refinements/modifications/improvements that are needed as a result of the user using the model. I don't expect SCS will be able to call upon ARS scientists on a frequent basis because of other demands on their time.

What happened and what, hopefully, will continue to happen? SCS people working to simplify, to convert to a language that SCS can understand, that is, developing an operational model. In this process, the developer and user work closely together to eliminate the bugs. Doing what, specifically?

I have the answer boiled down to one word: "simplicity." That is, developing simplified front-end and back-end programs.

FRONT-END - Interactive program that anybody with good soil and water knowledge can load; interactive, user-friendly software for micros to make parameter file development easy.

BACK-END - A user can tell the machine how data are to be presented, developing the displays that are desired. Once again, user-friendly software for report generation is needed.

These steps will help overcome reluctance to work with computers, significantly reduce coding time, and successfully permit comparison between resource management systems.

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Now let me move on to specifics with regard to CREAMS:

A point that I feel needs to be brought out is that CREAMS will not be obsolete when CREAMS2 is released. Quite the contrary, we'll be using both! CREAMS was originally designed for water quality assessments, but it is close to a complete resource model of a field. We are gaining much more insight into the erosion process and sediment and chemical transport. CREAMS2 will be/is a more complete resource response model.

Now for the quandary of which model to use. We're anticipating that in relative order of magnitude, CREAMS will cost 50¢ to run and CREAMS2 $5. Should we develop a flow chart which will help the user determine which to use? This question will probably become moot after a user becomes acquainted with the two.

To expand that thought, can this be accomplished only after comparative analyses are performed? Some, if not all of you scientists, know the answer, or at least have a good feel for it. You can easily down play this thought, but I feel the need to emphasize that we in SCS are practitioners; we like everything in neat little boxes, a form to fill out, because time and resources don't permit too much more. We're not modelers, we're not scientists. For successful use, we need a reasonably simple interactive program that will allow access by our field people.

CREAMS2 will address many of the areas of concern brought out during the CREAMS technology transfer effort. Since CREAMS2 has not been completed, tested, or released by ARS, we cannot fully quantify the model's capability. However, we can glean some items from the briefings we've had:

1. The model will function as one interactive model rather than three components of hydrology, erosion/sedimentation, and chemicals as in CREAMS. This interaction should be more responsive to the resource system; that is, crops on fields vs. land treatment effects on yields. Herein lies a resource management tool for disciplines other than water quality specialists.

2. Frozen ground can be simulated with the soil temperature routine that is driven by air temperature. However, some of my colleagues have expressed doubts that the model has yet arrived: "We need a super snowmelt generator and a way to look at rainfall on snow or frozen ground."

3. Crop yield can be simulated--again, a tool for other disciplines.

4. The soil layering is a plus--soil horizons can be coded as they occur in nature rather than by fixed strata. This allows the user to reflect abnormalities, such as plow pans. On the other hand, will 10 horizons be needed and will this confuse the user? This process, however, allows a better job of tracking water movement in the root zone.

5. Influence of animal waste on nutrient content in soil and water can be simulated. CREAMS values have to be loaded in small increments. This part of CREAMS2 is one of the best.

6. Nutrient contribution from green manure crops can be simulated.

7. Input coding is easier.

8. Although there is greatly expanded power in the irrigation segment, we're concerned about the irrigation routine because, under sprinkler systems, the entire field is covered at one time. Under surface irrigation, the tailwater situation isn't simulated; and it would be a plus to be able to find the trade-off between application and response where the amount of available water is less than that identified to refill the root zone.

9. A good method to compute N and P use is needed; that is, a good way to find the starting point for N and P. Some of my colleagues are nervous about the P algorithms. What bothers them I can't answer with specificity, but it is a flag.

10. Essentially, an entire program has to be run to obtain a single segment of output. My thrust here is to stylize the output media--printed or disc. It is not efficient to leaf through reams of output if you're only interested in pesticides.

11. We're anticipating that output can be more specific and preselected by the user. This hasn't been programmed; but, we've discussed it.

12. CREAMS2 will not simulate strip cropping, and we desperately need this in many parts of the country.

13. An error message system is needed as part of the program. It's rather aggravating to input large amounts of data only to find that the model will not accept it.

We in SCS have a good bit of internalizing to do on the CREAMS model. There is a piece of pie for the irrigators, one for the drainage folks, one for the plant science people, and one for the soil scientists--virtually a slice for every discipline within SCS. We must develop CREAMS in concert with all these disciplines. Training is essential.

We have some mechanical problems to overcome, such as getting the needed computational power--at this time, micros--to the users' location. Our present system is too cumbersome, one of transmitting data files to the Washington Computer Center (WCC) via Harris terminals. This approach requires a significant turn-around time, thus limiting the number of runs a user can make.

We're going to have to set up someone, working at the elbows of ARS scientists, to coordinate the work of technology transfer and, hopefully, have no other assignment. At least 2 years are needed to field test CREAMS2. This will be the debugging phase. SCS cannot expect the model developer to produce the perfect model for us. Publishing the model is one step; getting it operational is another giant step. Technology transfer is an absolute must!

In conclusion, once again, let me say how much we in SCS appreciate the dedicated efforts that ARS scientists have extended in the CREAMS development: the many hours of hard work, travel to help SCS train our people, and work to debug the system. ARS scientists are to be commended for their grasp of SCS operating conditions and for their knowledge of field data available for our use. Those scientists who participated in the technology transfer effort and those who continue to do so have our highest respect for their patience, understanding, and donation of their time to make this effort successful.

SMALL WATERSHED MODEL

Carlos V. Alonso and Donn G. DeCoursey[1]

INTRODUCTION

The Small WAtershed Model (SWAM) described in this paper was developed to show the effect of changes in land use and management on the hydrologic, sediment, and chemical responses of a small watershed. The development is in response to PL 92-500 and more recent needs for models that describe the physical response of small watersheds. Planners responding to questions concerning nonpoint sources of pollution and the effect of watershed management on all aspects of the physical state of a watershed needed a causal type model that would describe these things. The SWAM model is the second of a series of models developed in reply to these needs.

Agricultural Research Service scientists responded to the need to develop such causal models by development of the Chemical, Runoff and Erosion from Agricultural Management System (CREAMS) model (Knisel, 1980) and the initiation of a plan to produce two other models. The CREAMS model is a field scale simulation of hydrologic, sediment, and chemical response. The small watershed model, described in this paper, is the second in this series. It uses a dynamic version of the CREAMS model to develop the response from source areas, and routes these responses through the channel system. The effects of both surface reservoirs and groundwater are included. The third model in this series is to be a basin scale model of these same processes.

The small watershed model described in the following pages was developed, as described, because:

1. We wanted an accurate representation of watershed response when it is influenced by movement of water through surface channels, through reservoirs, and through groundwater zones.
2. We wanted an accurate representation of the physical and chemical processes without subjective distortion due to lumping, curve fitting, and so forth (SWAM is not just another yield model).
3. We wanted to establish a modeled environment in which new concepts and ideas could be tried as realistically as possible.
4. We wanted to provide a model that would be a reliable data generator for use in developing simpler application versions of SWAM and the basin scale model. The massive amount of field information that would be needed to develop such models is not economically feasible; however, a verified version of SWAM could be used to generate such data.
5. In order to provide the information in objective 4, the model must be able to generate consistent and accurate estimates of short-term through long-term statistics (event, daily, monthly, et cetera) as well as correct simulations of localized and distributed processes.

The balance of this paper discusses the capabilities of the model and the structure of the associated system code as they stand at the present time (October 1983). An early description of the model was presented by DeCoursey (1982).

BRIEF OVERVIEW OF MODEL'S CAPABILITIES

The small watershed model is designed to show the effect of changes in land use or management on the hydrologic, sediment, and chemical response of agricultural areas not greater than 10 km^2 in size. This model is a continuous simulation system driven by precipitation and other meteorological inputs. In designing this system we look upon a watershed as a continuum upon which a set of constituents move, interacting with each other and with the agricultural environment. The constituents are water, sediment, and chemicals (nutrients and pesticides). The flow of these constituents through the environment and their mutual interaction form the processes simulated by the system.

A real watershed contains a continuous spectrum of constituents, processes, and environmental conditions. Digital simulation of such a continuum is carried out by introducing a discrete representation of the watershed. This is done by subdividing the watershed being modeled into interconnected segments, each segment representing a different portion of the watershed, having relatively uniform properties, and where conditions may be characterized by a unique set of processes. In this manner, elements of the same type embody the same collection of processes and are represented by sets of parameters having identical structure. Variations between segments are easily incorporated by variations in the values of the parameters.

Four distinct types of segments are identified in SWAM: source areas (the various fields in the watershed), channels, reservoirs, and groundwater. Dynamic schemes route water, sediment, and chemical outputs from all source areas through the channels and reservoirs in the watershed. A groundwater component that includes transport of dissolved constituents provides estimates of groundwater return into channels and reservoirs (figure 1). All model components make use of metric units. A brief description of these components follows.

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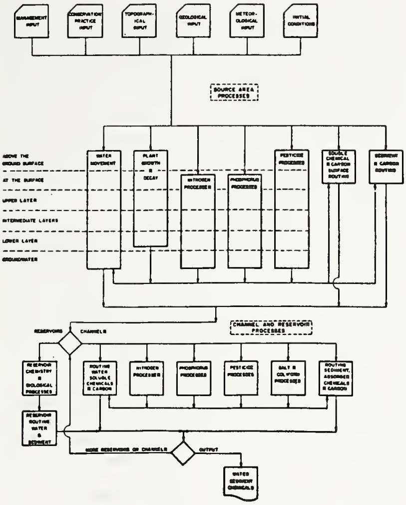

Figure 1.--Small watershed model (SWAM).

Source Area Processes

The dynamic version of CREAMS2 provides a continuous record of each field's response. This model incorporates simulation of both surface and subsurface processes and is described in detail by Smith (1983).

Channel Processes

Using input data describing a channel segment and the hydrographs of all upstream inputs (channel and reservoir outflows, groundwater returns) and lateral inputs (outflows from source areas and groundwater returns), longitudinal stage profiles and flow distributions are computed using one of several one-dimensional schemes. If the reach is upstream from a reservoir or in a backwater situation, water is routed using a diffusive wave scheme. If the flow is unobstructed, low flow conditions develop; or if the reach runs partially dry, routing is based on a kinematic wave scheme. When all inflows remain constant over a 1-day period, flow in the channel is treated as steady. The cross section of the reach is split into interconnected subchannels whenever hydraulic conveyance varies significantly over the cross section or whenever obstructions, such as deposition bars, cause the flow to bifurcate. This feature permits the model to approximate water movement in and out of channel banks, but transfer between subchannels is ignored. Channel losses are simulated and infiltrated water goes into deep storage.

Continuous tracking of daily stream temperature is needed as input to downstream reservoirs and for evaluating temperature dependent parameters. SWAM predicts average daily water temperature throughout the channel network. A dynamic component simulates longitudinal variations of temperature along each channel reach. The model accounts for the following heat energy gains and losses: heat energy carried by inflows and outflows, solar energy, stream evaporation, and conductive and convective heat losses. Solar energy is computed as a function of watershed latitude, topographic features, time of the year, cloud cover, atmospheric and water surface backscattering, and topographic and riparian vegetation shading.

The composition of sediment transported through a channel reach is dependent upon the characteristics of the bed material, the transported load and flow conditions. Sediment is routed using a total-load Lagrangian scheme that eliminates the need for distinguishing between celerities of bed and suspended loads. Channel aggradation, degradation, or equilibrium processes are simulated as a function of residual transport capacity. This is based on magnitude and composition of the sediment load and flow carrying capacity of individual material fractions. Rates of sediment deposition or bed material scour are used to establish new load composition, bed elevation profile, and material composition of the active bed layer. When this layer is composed of material too large to be transported, it develops into an armor layer.

Inputs of nitrogen, phosphorus, and pesticides are routed with a mass-conserving Lagrangian scheme that simulates longitudinal variations of chemical concentrations due to additions from external sources, transmission losses and sediment deposition. Transport by longitudinal dispersion and the uptake and release by bank and bed sediments are not presently modeled. As they move through the reach, merged loads are redistributed into dissolved and particulate forms as discussed in the following paragraphs.

The nitrogen model handles nitrates and sediment-associated nitrogen. For practical purposes, nitrates are not adsorbed but move only in solution. Organic nitrogen moves with the organic fraction of the sediment. Ammonia, which is computed as part of the sediment-associated nitrogen, is transported mostly adsorbed and is separated on the basis of an equilibrium sorption isotherm.

Sorbed and soluble phosphorus interactions are described by a linear equilibrium isotherm that quantifies the effect of combining phosphorus-rich sediments with poor ones. Mineral surface is the sediment property controlling phosphorus sorption. Fixed-phosphorus shifts occur when inflows of greatly different labile or soluble phosphorus concentrations are mixed.

Pesticide treatment is similar to that of phosphorus, except that no pesticide fixation

takes place and organic carbon is the sediment property controlling sorption. The interaction of pesticides under equilibrium conditions and their separation into dissolved and adsorbed forms are described by a linear sorption isotherm.

Reservoir Processes

Reservoirs and small impoundments, such as farm ponds, probably have more impact on the water quality in a channel system than any other structural or land use conservation practice. Therefore, this component incorporates a very detailed treatment of impoundment processes. Given initial temperature, suspended sediments, dissolved solids and chemical distributions, and inflow data composition, the model simulates daily changes that take place in the temperature, suspended sediment, and dissolved solids profiles. The model takes into consideration density currents and changes in thermal stratification that develop as inflows enter the impoundment. Inflow data can include outflows from source areas and channel and groundwater tributaries.

After changes in the profiles are calculated, chemical and biological process changes are simulated. Phosphorus processes include plankton uptake, decay, and release as well as sediment sorption-desorption isotherms in each density-stratified layer.

The nitrogen submodel simulates layered distributions of nitrate, dissolved and adsorbed ammonium, and organic nitrogen concentrations. A linear sorption isotherm for ammonium is computed for each layer as a function of specific surface of suspended sediment and sediment organic matter. Transformations and interconversions among the nitrogen compartments are mediated by plankton and microbial processes.

Pesticide processes simulated include a sorption-desorption isotherm balance between the soluble fraction and that adsorbed on the suspended sediments in each layer. In addition to adsorption and deposition, pesticide concentrations are reduced by first order decay. This decay is dependent upon the cumulative effect of partial decay processes specific to each pesticide. Other incorporated processes which may or may not be important for a given pesticide are volatilization, photolysis, hydrolosis, and biological decomposition.

Outflow from the reservoir at the end of each day (if there is any) includes temperature, suspended sediments, and chemical loads. These constituents are input to the downstream channel reach.

Groundwater Processes

Groundwater movement into the channel and reservoir system is based on the streamtube concept. Low flow conditions in the watershed are used to identify those reaches where groundwater enters channel and impoundment reaches. Groundwater wells are used to establish the groundwater divide; then, representative flow paths are drawn. The flow paths are grouped into representative streamtubes for each of the receiving surface reaches, and the input is calculated on a daily basis. Flow into the receiving channel or reservoir is a function of the saturated conductivity, porosity, length of the groundwater streamtube, phreatic head at the divide relative to the water surface elevation in the channel or reservoir reach, and thickness of the aquifer at the receiving reach. Both convergent and nonconvergent flow are considered. Flow in the saturated flow zone is assumed to be sufficiently parallel to the confining layer for the Dupuit-Forcheimer approximation to apply. This theory is used to obtain the initial profile of the phreatic surface. Water percolating from the unsaturated flow zone is added to saturated flow storage. This raises the elevation of the groundwater table, thus changing the flow rate and rate of groundwater flow recession. If a streamtube crosses several source areas, the overall recharge from all fields is averaged across the entire length of the path to get a single, weighted-average increase in the water table level. Any chemicals, such as nitrate solution, that the percolating water may carry into the groundwater are assumed to be uniformly mixed with the groundwater below the source area. These concentrations are mixed with inflowing water from up-gradients and down-gradients in the same way. This simplified approach to estimating the quantity and quality of groundwater provides daily inputs that are added to surface runoff and routed through the channel and reservoir system.

Input Data

Data needed to operate the SWAM model includes information on land management operations, conservation practices, topographical and geological characteristics, meteorological inputs, and antecedent conditions.

WATERSHED DISCRETIZATION

As already indicated SWAM simulates a watershed by subdividing the prototype into interconnected segments, each segment characterized by a uniform distribution of physical properties and modeling parameters. The simulation handles the processes occurring within the segments and the transfer of information and constituents between them. Each segment is simulated for an extended period of time before moving to the next one. To allow for this, the user defines a computational sequence such that all information required by any segment comes from segments already simulated. This approach provides the basis for subdividing the watershed.

The first step in discretizing the watershed is to divide it into interconnected source area, channel, reservoir and groundwater segments. In SWAM a field is regarded as an area with uniform land use, even though the soil may or may not be uniform. Heterogeneous areal distributions of soil properties are at present being replaced by area weighted averages. Variations in soil properties are only allowed between soil layers. In general fields are bounded by ridges, boundaries with other fields, conservation structures, and intercepting stream segments. In the last case, the fields are also bounded laterally by the flow lines passing through the ends of the stream segment. Areas covered by roads and buildings are presently ignored and treated as noncontributing zones.

Channel segments are selected such that they may be treated as prismatic elements having uniform material and hydraulic properties. Each channel segment is assigned a cross-sectional shape representative of the segment's storage properties. Outflows from other segments can enter a channel in two ways: as uniformly distributed lateral inflows from source areas and groundwater contributions and as point inflows from upstream channels and groundwater returns. Reservoirs are treated as single segments and accept the same type of inflows channel segments do.

In order to discretize the saturated flow region, the groundwater flow lines are collected into a set of noninteracting streamtubes, both parallel and convergent, that carry water and chemicals to the receiving surface flow segments. Each streamtube becomes a groundwater segment recharged by the unsaturated outflow from one or more fields. To facilitate identification of the source areas generating the individual recharges, the groundwater segments are further subdivided into partitions and each recharge is assigned to a receiving partition. In the case of non-point groundwater returns the width of the segment is controlled by the length of the receiving channel. The subtended angle and partitions assigned to each one of the segments are established based on continuity considerations; namely, the combined area of all the groundwater segments must equal the combined area of all the contributing source areas.

The next step in the discretization process is to define an appropriate computational ordering, or sequence, such that all inflows required by any segment at any stage of the simulation come from segments already simulated. This sequence is readily determined by following the flow path through the cascade of segments as established by the logics of gravity and flow continuity. The order in which the segments appear in the flow path defines the computational sequence. The following heuristic rule is used to establish this ordering: The number "one" is assigned to one of the most upstream segments in the cascade and then the flow path is followed down the cascade. If the next segment is not on a tributary branch, it is given the next consecutive number; if the next segment is on a tributary branch, the next consecutive number is assigned to the most upstream segment on the tributary. This process is repeated until the watershed outlet is reached and all segments are numbered.

During a simulation run the outflows identified by the segment numbers are stored in temporary buffer files. The outflows from some segments are retained in storage, while other segments are processed until the junction is reached where the stored flows combine. The buffer files used to store the outflows are then released and used by other segments.

In general, the order in which the segments are processed affects the maximum number of buffer files needed during a run. Therefore, the computational sequence must be established so as to optimize the use of temporary storage. Further optimization is attained in SWAM by merging outflows from tributaries of the same type before they are processed by the receiving segment. By taking advantage of these optimizing features only a few buffer files are needed to simulate watersheds containing a large number of segments.

SYSTEM SOFTWARE CONFIGURATION

The SWAM system consists of three subsystems that are run separately: an input file generator, the SWAM simulator proper, and an output report generator. Data such as formatted texts, parameter tables, messages, and so forth, which these programs need to perform their work is kept in a separate file that is part of the SWAM package. This organization simplifies code development, code maintenance, and data updating and reduces the amount of resident memory required to execute a SWAM run. The programs are written in ANSI FORTRAN-77. Following are brief descriptions of these programs.

Input File Generator

This is the entry point for every new SWAM simulation. The program is used to generate a binary file--named INPTFL--containing all data other than weather input needed to simulate a given watershed. Weather data are stored in separate sequential formatted files.

The watershed data are entered from an interactive device and output to the binary file. The user can also use this program to make changes in any data entry contained in an already existing SWAM input file and to display or print out the entire file or selected parts of it. The user is led step by step through all these functions by messages generated on the interactive device's display.

The input consists of data subsets comprising the computational sequence, input parameters, and initial value files for each segment, logical names of weather files used by the source

areas, and time block sequence (discussed in the following section). The program prompts the user for these inputs by displaying input text lines preceded by appropriate explanatory headings. Input text lines, headings, messages, et cetera, are stored in a permanent direct access formatted file--named DGENFL--and are retrieved and displayed by the program as they are needed. After the user enters each individual input, the program verifies that the entry falls within the allowable range defined by the corresponding minimum and maximum values. If it does not, an error message is generated, and the user is prompted to enter a new value. On the other hand, the user is permitted to accept default values, except for data entries with negative defaults. In these instances the user must enter the expected value for program execution to resume. After all entries for a data subset are completed, they are output to the direct-access binary file INPTFL with the addition of key offsets to start and end records of each data subset.

Next, the program proceeds to augment the input data by computing all those parameters and initial values that can be derived from input data. For example, the program derives channel hydraulic properties from cross-sectional survey data, soil water parameters for layered soils, the initial phreatic surface profile in groundwater segments, and so on. The augmented data is output to the binary file and becomes part of input file of the corresponding segments.

Once the input file is completed, it can be used to perform repeated simulations of the parent watershed under different climatic input or it can be modified as desired to simulate the effect of various antecedent conditions and land management practices.

SWAM Simulator

The overall organization of this program is shown in figure 2. It has been organized around two basic concepts: the process of operations following an optimal computational sequence and the use of time blocks.

To simulate any given segment in a watershed, SWAM must handle all the processes occurring within the segment as well as the transfer of information into and out of the segment before moving to simulate the next segment in the computational sequence. The activities performed on any segment can be grouped into three distinct functions: access the inflows from all contributing segments, operate on these inflows to generate the response of the segment, and output the resulting outflows. The user indicates indirectly, via the computational sequence, the devices allocated to inputs and outputs, and the system moves this information accordingly between the devices and the operating subroutines. These functions are common to all segments and are collectively identified as an "operation." It is

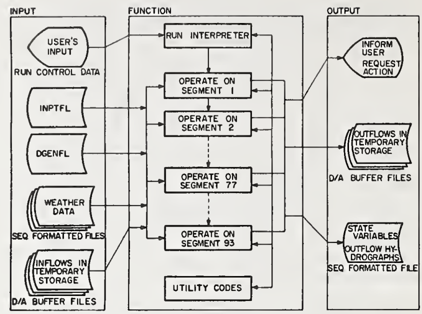

Figure 2.--Overview diagram of SWAM simulator.

obvious from the discussion on watershed discretization that a simulation can be viewed as a series of operations performed in sequence, with the same operations applied repetitively to all segments of the same type.

During an operation a segment is simulated for a specified period of time. Input data is read from two files: the INPTFL binary file containing all the data describing the segment and a formatted sequential file containing weather parameters and breakpoint rainfall data (this file is only used by source area segments). When the operation is completed the segment's outputs are written to temporary direct access binary files (buffer files). These data in turn become the input to the receiving segment. If the simulation period is too long a large amount of temporary storage is required to retain output from one or more segments until the data are used as input to a downstream segment. This problem is overcome by dividing the overall simulation period in a fixed number of subperiods called time blocks that can be handled in sequence. This requires dividing all the precipitation files in a number of identical time blocks. At the end of each time block the segment's state variables are transferred back to the same section of the INPTFL file which they came from. In this manner the values of all the variables are ready for use when the segment's simulation is restarted for the next time block.

A simulation run is thus reduced to a series of operations which are repeated, following the same sequence for each time block. The sequences of operations and time blocks are specified in the input file and are supervised by the Run Interpreter. This is a group of subprograms which read and translate the user's input into instructions used by other parts of the system and transfers information to the system regarding the operations to be performed. Run Control Data--such as assignment of logical

unit numbers to I/O devices, start and end dates of simulation, routing and output options, and so forth--are entered from an interactive device at the beginning of each individual run. Routine tasks common to two or more program units are grouped under the name of Utility Codes. At the end of each time block, the system transfers output data selected by the user to a formatted sequential output file.

Individual operations are performed by groups of subprograms that handle all the manipulations of inputs and outputs associated with the simulation of individual segments. There are four different groups corresponding to the four types of segments used in SWAM. These groups perform most of the work in a run. For illustrative purposes, the functions performed by a channel operation are depicted in figure 3. The primary task of this subprogram is to ensure that the various functions are called in the correct order and that the associated inflows, parameters, state variables, and outflows are input and/or output at the required points. The hierarchy of functions are explained in the following paragraphs.

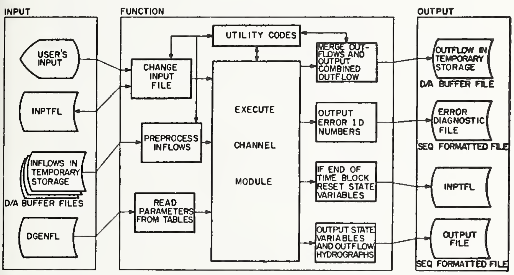

Figure 3.--Overview diagram of channel operation.

Input parameters and initial conditions are read, converted to internal format, and stored in the section of resident memory allocated to the operations group. At the beginning of each time block the user can interactively access the input file and change any data entry in the file. This capability can be used to alter parameters, state variables, scheduled management operations, et cetera, during the course of the simulation without having to start the run over again.

The program decides which inflows and outflows are required and assigns to them the proper buffer files.

Properties of crops, tillage operations, soils, sediments, nutrients, and pesticides are retrieved as they are needed from tables built into the DGENFL file.

When all the foregoing information is in place, the channel module is executed. This program unit invokes all the appropriate subroutines that make up a channel run. Each time this module is called, a channel operation is performed on the inputs for a time block period. During this operation the state variables are continuously updated and the channel outflow output to the assigned buffer file. Whenever an error is encountered during a simulation, a code number is generated and copied onto an error diagnostic file. The error messages and explanations associated with every error code are contained in a separate file to minimize the use of core storage. The user needs only to match the code numbers with the list of error messages to establish a diagnosis.

When the channel module's task is over, the program decides whether the outflow should be merged with the outflow from another channel or reservoir segment and, if so, calls the Merge subprogram. This is a group of subroutines that allow for the merging of arbitrarily shaped hydrographs having different durations and carrying loads with dissimilar sediment and chemical compositions.

Finally, and before returning control to the Run Interpreter, the updated state variables are written back to the same location of the INPTFL file which they came from. This information is restored to the core area assigned to the channel operation when this is resumed to simulate the next time block.

Output Report Generator

This is a stand-alone program that generates various levels of outputs, depending on the output options selected by the user. The program reads data from the output sequential file created by the Simulator and invokes all the subroutines that make up a report generation run.

In order to provide the user with comprehensive information, the operational version of this program will eventually include all coding needed to echoed input data, list state variables and plot outflow histograms of selected segments, generate tables of daily, monthly, and annual statistics, perform space-and-time correlation analyses of various types, et cetera.

SUMMARY

SWAM simulates a small agricultural watershed by dividing it into an ordered cascade of interconnected source areas, channels, reservoirs and groundwater segments.

Outputs from all source areas are routed through the channel and reservoir systems to the watershed outlet. The dynamic version of CREAMS2 provides a continuous record of water, sediment, and chemicals from each source area in the watershed. A dynamic channel routing scheme routes the water and sediments, calculating both

bed aggradation and degradation; sediment exchange between the sediment load and the bed layer is also included. The reservoir model calculates profiles of temperature and sediment concentration as well as the effects of biological activity on nutrients levels. A groundwater component routes water and chemical recharges to the channel and reservoir system. Most of the significant chemical balances and changes are considered as the flow moves from segment to segment.

The SWAM system is organized into three subsystems that are run separately. An input file generator program is used to create a file containing all the input data that describe the watershed. A simulator program performs all the operations that constitute a simulation run. This subsystem is developed around the idea of dividing the simulation period into a sequence of time blocks and performing the operations in a specified order for each time block. An output report generator program creates various levels of outputs, depending upon the selected output options.

ACKNOWLEDGMENTS

The development of SWAM is an ARS team effort to which many people have and are contributing. Roger E. Smith developed much of the dynamic version of CREAMS2. He has received MUCH support from other members of the CREAMS team. Carlos V. Alonso is responsible for the development of the channel model and for the design and development of the overall SWAM software system. Harry B. Pionke has been responsible for coordinating development of the chemistry components' behavior and transport through the channel system; Harry M. Kunishi, Ronald R. Schnabel, and Roger J. DeAngelis have significantly contributed to this effort. Fred D. Theurer (U.S. Soil Conservation Service) contributed the instream water temperature model. Frank R. Schiebe, Charles L. Gallegos, and Ronald G. Menzel are responsible for the reservoir model. Donn G. DeCoursey and William J. Gburek are responsible for the development of the groundwater component. James B. Burford, Michael R. Murphy, and Ralph T. Roberts are assembling the data sets needed for testing.

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SOIL CONSERVATION SERVICE COMMENTS ON ARS SMALL WATERSHED MODEL (SWAM)

Bernard A. Shafer[1]

INTRODUCTORY REMARKS

The Agricultural Research Service (ARS) is to be commended for its farsightedness in accurately predicting the need for a progressive series of models, ranging from field scale to basin scale, addressing agricultural systems, and capitalizing on the tremendous computing power available today. CREAMS (Knisel 1980) and SWAM (DeCoursey 1982) both represent state-of-the-art models that produce usable results from available data. However, it is important to note that these models will not be fully utilized within our agency until a significant portion of the Soil Conservation Service's (SCS) Information Resource Management System long-range plan is in place and functional. Specifically, technical specialists must have ready access to hardware, software, and multiple data bases and must receive substantial training before the real benefits of models like CREAMS or SWAM will be manifest. Reliable and responsible use of models like SWAM will require a commitment to continuing education for SCS staff to keep abreast of the level of technology embodied in conceptual modeling approaches.

The entire field of modeling is a difficult balancing act where multiple factors must be weighed simultaneously. These factors include (1) purpose, (2) accuracy required, (3) complexity, (4) difficulty of application, and (5) consistency of results. It is encumbent upon the model developer as well as the end user to consider these factors carefully before committing to any modeling activity. No single model will meet all the expectations of every potential user. SWAM can and should be one of the technical tools available to the SCS.

As we move from relatively easily understood empirical and statistical models to physically based conceptual models, we are challenged to increase our technical knowledge and skills. Unless we collectively accept and meet that challenge, we will never become responsible model users and never realize the potential such models offer for solving resource allocation and conservation application problems. We can expect that less reliance will be placed on fully deterministic "cook book" approaches; while fuller understanding and acceptance of the stochastic nature of physical processes will come with education and utilization of models like SWAM.

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POSITIVE FEATURES OF SWAM

SWAM is an ambitious effort to integrate multiple processes in a systematic fashion that addresses pressing conservation problems on a small watershed scale. As such, it is a natural evolutionary step from the CREAMS field-scale model. As presently conceptualized, designed, and undergoing testing, it is a tremendous intellectual and technological undertaking. It is the first truly comprehensive, agriculturally oriented natural resource assessment model on a watershed scale that attempts to logically link related physical processes using state-of-the-art research results. As such, it will be valuable for both operations and research. The effort to date is worthy of commendation and certainly of continued support.

The following points are especially worth noting:

1. SWAM's modular design should facilitate enhancement of existing process modules, as well as provide the framework to easily add new process modules which derive from current research.

2. SWAM software design appears to be computationally efficient and memory conservative.

3. A high degree of flexibility is evident in the model, providing users an opportunity to customize computational paths. This feature, however, is a two-edged sword since it increases complexity.

4. SWAM is designed to run on present generation minicomputers. Since these machines are anticipated to be available in greater quantity and to be accessible to all SCS personnel in the next 5 years, we can be confident that the model will be utilized.

5. Initial complex process definition leading to later simplification based on sensitivity and validation tests is sound.

6. An interactive input file generator eases the task of entering requisite data and minimizes the need to remember and use explicit formatting rules.

POINTS TO PONDER

The following items have been identified as issues deserving further attention:

1. Metric unit use may serve best in a research environment and be useful for exporting the model to foreign countries. However, consideration should be given to supporting the model in both English and metric units thereby permitting the user to choose the system with which he is most familiar.

2. Model input and calibration requirements are formidable; an estimated 40 calibration parameters or descriptors are required. Close scrutiny of the complexity in individual

processes employed in the model seems warranted to simplify the model for real-world application by an operational agency. Careful evaluation of the results of sensitivity analyses should help identify where the model could be simplified without compromising its performances. Where feasible, provisions should be considered for extracting parameter values and input data from readily accessible automated data bases to avoid unnecessary manual key entry. Examples of data bases that could be accessed include soils, streamflow, and vegetation data.

3. When the user is entering parameter values interactively in Input File Generator, it would be useful for him to see the acceptable range for each parameter (that is, maximum and minimum values), since they are already contained in the software.

4. There is no singular solution to sequential segmentation during the discretization process. The discretization process appears to be very complex; it presupposes a user having a high degree of familiarity with the model and a wealth of experience in order to define the multitude of segments in the appropriate order to produce meaningful simulations. The so-called heuristic rule leads to a multiplicity of interpretations dependent upon the skill and background of the user. The user's perception of how to define a computational schedule for the segments appears to greatly influence results of any simulation. More definitive guidelines for defining source area, channel, reservoir, and ground water segments would be helpful. In particular, the current method advocated to define source area, channel, reservoir, and ground water segment's relationships to one another will likely cause much confusion for an inexperienced user.

5. As the model is developed and tested, consideration should be given to creating a simplified operational version for field trials that does not require the large volume of reference material and data bases from research watersheds. At the same time, a more detailed and physically descriptive version of the model that includes new simulation modules and provisions to use data only available on research watersheds should continue to be supported for the research community.

6. Climatological data sets are among the fundamental input data sets needed to drive the model. It is difficult to obtain or access climatological data sets in machine-readable form from a single source as a general rule. Before models like SWAM will be widely applied, provisions for automating climatological data access must be made. The National Climatic Data Center is making some progress in this area, with tentative plans to provide user access via dial-up communications. SWAM should have a data access and preprocessor component that could retrieve data using the dial-up link being proposed.

7. SWAM should be subjected to a limited amount of beta testing by independent groups to find bugs and suggest improvements prior to release for general use. Beta test centers could also be useful in preparing operational model documentation for users. SCS National Technical Centers are suggested as possible candidates to perform this task since they are staffed with technical specialists trained in many disciplines.

8. Frozen soils can have a large influence on both runoff and erosion processes. It would be desirable to make some further effort to address this condition in SWAM.

9. Some investigation into the potential application of remotely sensed data from the Thematic Mapper (TM) on Landsat should be undertaken to see how such information might beneficially be utilized in SWAM. TM data are of sufficient resolution to be potentially valuable in small-watershed-scale modeling.

10. End user training needs to be recognized as a critical function, and a strategy should be developed to provide both initial and continuing educational support. This task should be a joint effort between the ARS and SCS. Both agencies should allocate sufficient resources to the technology transfer aspect of SWAM. Without a commitment to the training and technology transfer activity, SWAM will simply be another research tool that never made the transition to operational application.

CONCLUSIONS

SWAM is a promising tool for evaluating natural resource assessment problems and impacts at an improved level of detail and areal extent. ARS and SWAM architects are to be congratulated for their attempt to bring together research results from diverse areas into a systematic, comprehensible process simulation model aimed at improving our understanding of complex physical interactions as well as providing an operational tool for technical specialists in action agencies such as SCS. This effort deserves continued funding and support by both agencies.

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SPUR - SIMULATION OF PRODUCTION AND UTILIZATION OF RANGELANDS

J. R. Wight and E. P. Springer[1]

INTRODUCTION

The SPUR Model has been described in a U.S. Department of Agriculture, Miscellaneous Publication (Wight 1983). Discussions presented herein under headings containing the terms "component" and "consumers" have been taken directly from chapters in that publication. The authors of those chapters are herein identified parenthetically after the appropriate headings. State variables and input variables and parameters for SPUR are listed by component in the appendix.

An ARS range modeling effort was initiated in November 1980. The general objectives of this modeling effort were to enhance the application of modeling technology in ARS range research and to develop a comprehensive model or models for management and research use. The SPUR model reported herein is a product of this modeling effort. It represents the combined efforts of both ARS and non-ARS scientists working at several locations. Actual work on the model was begun following a planning workshop in May 1981. Interfacing of the components into a comprehensive model was accomplished at the Northwest Watershed Research Center in Boise, Idaho, during the summer of 1982. Model components were developed using currently available information, including models such as ELM (Grassland Simulation Model) (Innis 1978), CREAMS (A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel 1980), and EPIC (Erosion Productivity Impact Calculator) (Williams et al. 1982). In general, the components in SPUR represent the state of the art in their application to rangeland ecosystems.

SPUR is a physically based, rangeland simulation model developed to aid both resource managers and researchers. It is composed of five basic components: (1) climate, (2) hydrology, (3) plant, (4) animal (both domestic and wildlife), and (5) economic. A subroutine is available to simulate the impacts of either grasshopper destruction or control. At present, this subroutine is an option and is not initiated by any model component.

Two versions of SPUR have been developed: A grazing unit or pasture scale version and a basin scale version. The pasture scale version can simulate the growth of up to seven plant species or species groups. These species or species groups can be grown on up to nine different range sites within a grazing unit. It can accommodate the resolution of the animal component to differentially graze a pasture based on the combined effect of different preference vectors. It provides pasture or allotment level managers a method to simulate growth and grazing of the major plant species and animal production. The pasture scale version also provides erosion, runoff, and peak flow indices for relative comparisons as related to range sites and to management options.

The basin scale version is somewhat more complex; it provides a means of predicting quantities of runoff and sediment yield for basins of up to 2500 ha with up to 27 hydrologic units (drainages adjacent to a channel), and it retains the ability to simulate plant growth, grazing, and beef production. However, the resolution of these components is diminished relative to the pasture scale version. The basin scale version uses the watershed as a management unit and is designed to answer the questions of the land manager.

CLIMATE COMPONENT (Hanson and Richardson 1983)

SPUR is driven by daily inputs of rainfall, maximum and minimum temperatures, solar radiation, and wind run. These can be obtained from weather records or by stochastic generation within the climatic component.

The climate component subroutine contains three options for utilizing available climatic data or generating a climatic record:

1. Read in daily precipitation, maximum and minimum air temperature, and solar radiation from a location record.
2. Read in daily precipitation and generate daily maximum and minimum air temperature and solar radiation.
3. Generate daily precipitation, maximum and minimum air temperature and solar radiation.

The subroutines in SPUR can utilize climatic data for only one location on a field or watershed. Daily wind speed is always generated.

The climate component is based on the Weather Generator model (WGEN) and is the same as the climate component of EPIC. The model procedures are described by Richardson (1981). Several assumptions have been made that simplify the use of the model, and a wind component has been added. Model parameters required to generate new sequences of weather variables have been determined for many locations in the United States and will be listed in the SPUR Users Manual. A program is also available to compute the required generating parameters if sufficient data are available.

WGEN provides daily generated values of precipitation, maximum temperature, minimum temperature, solar radiation, and windspeed for an n-year period at a given location. The model is designed to preserve the dependence in time, the internal correlation, and the seasonal characteristics that exist in actual weather data

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for a location. Precipitation and wind are generated independently of the other variables. Maximum temperature, minimum temperature, and solar radiation are generated, depending on whether the day is wet or dry.

HYDROLOGY COMPONENT: UPLAND PHASES (Renard et al. 1983)

The hydrology component of the model is designed to use inputs from the climate component and produce outputs unto its own (for example, runoff and sediment yield) or inputs for other components of the model (for example, estimates of available soil moisture for forage production and water for grazing animals). The hydrology component is divided into three parts: an upland phase, a snowmelt phase, and a channel phase.

The upland phases of the hydrology model for SPUR draw heavily from a model called SWRRB (Simulation for Water Resources in Rural Basins)[2], which has been modified and improved to consider the essential features known to affect the hydrologic response of rangelands. THE SWRRB model includes the major processes of surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage, and erosion and sedimentation. The well known curve number technique (USDA 1972) is used to predict surface runoff for any given precipitation event because (1) many years of use have given confidence in its validity, (2) it relates runoff, soil type, vegetation, land use, and management, and (3) it is computationally efficient. The use of rainfall data for short time increments (minutes and/or hours), which are required with infiltration equations to compute precipitation excess, are not generally available for most areas of the United States, and especially not on the rangelands with the orographic precipitation effects, sparsity of recording raingauges, and so forth. Finally, daily rainfall estimates are computationally more efficient than similar operations with shorter time increments.

HYDROLOGY COMPONENT: SNOWMELT (Cooley, Springer, and Huber 1983)

The snowmelt component of SPUR was developed by Eric Anderson at the National Westher Service Hydrologic Research Laboratory (Anderson 1973). Anderson's model, referred to as HYDRO-17, is a conceptual model of the physical processes affecting snow accumulation and snowmelt, which Anderson considers mathematically significant. Air temperature is used to index energy exchange across the snow-air interface. This is not the same as the degree-day method, which uses air temperature as an index of outflow from the snowpack. HYDRO-17 explicitly accounts for freezing of the melt water due to a heat deficit and the retention and transmission of liquid-water, both of which cause snow cover outflow to differ from snowmelt.

[2]From Williams, J. R., and A. D. Nicks. 1983. SWRRB, A simulator for water resources on rural basins. Submitted for publication in Amer. Soc. Civil Engin., J. Hydraul. Div.

HYDROLOGY COMPONENT: WATER ROUTING AND SEDIMENTATION (Lane 1983)

The computational structure of the water routing and sedimentation subroutines follow the stream channel network from upland areas to the watershed outlet. Each channel can receive runoff and sediment from any combination of upland areas and/or one or two input channels.

Water Routing

Channel routing uses a double-triangle hydrograph approximation reported by Lane (1982a). Hydrograph characteristics are determined from geomorphic characteristics of the watershed, and procedures are included to estimate the effect of transmission losses on runoff volume and peakflow.

A piecewise normal approximation is used to calculate hydraulic variables for sediment routing. The hydrograph is broken into equal time increments, and normal flow is assumed over each time interval. The Manning equation is used to compute flow depth, velocity, and hydraulic radius for each time interval. All calculations are assumed to occur in a rectangular channel.

Sediment Routing

The sediment load is divided into suspended particles less than 0.062 mm in diameter, and bedload, particles greater than 0.062 mm. Only the bed material has a class size distribution associated with it. The model assumes transport capacity limiting conditions. The transport capacity of the bedload is computed with a modified Duboy's equation and the suspended load transport capacity is determined from a modified Duboy's equation and the suspended load transport capacity is determined from a modified Bagnold equation (Lane 1982b).

PLANT GROWTH COMPONENT (Hanson, Parton and Skiles 1983)

The primary producer model simulates the dynamics of phytomass (plant biomass) and nitrogen in the soil-plant system. There are seven phytomass and eight nitrogen state variables in the model. The carbon and nitrogen flows are controlled by using the maximum reduction technique. The model is designed to run on daily time steps.

Abiotic variables used to drive the plant growth processes include air temperature, precipitation, soil water potential, solar radiation, and daily windrun. Bulk density of the soil is also used by the model.

For the SPUR model, amount of phytomass on each day is required output from the primary producer model. Species-dependent state variables in the phytomass and nitrogen submodels are green shoots, live roots, propagules, and standing dead. Dead roots, litter, soil inorganic nitrogen, and soil organic matter have no species identity. (For a more detailed discussion of the plant component see Hanson et al. in this volume.)

LIVESTOCK COMPONENT (Rice, MacNeil, Jenkins, and Koong 1983)

The livestock component of SPUR was designed to simulate the dynamic impact of grazing on rangelands and livestock response. The major concepts included in the component development were (1) the effects of livestock grazing on herbage composition and production are the result of the selective removal of herbage by livestock and the amount and distribution of excretal return of nutrients, and (2) livestock response to a rangeland is the function of herbage quantity and nutrient quality, herbage species, and the site or location within a grazing area. The herbage supply provides two elements, standing biomass and nitrogen content, for the green and dry herbage classes.

The sequence of model flow calculations on a daily time step is as follows: Insect consumers exercise their demand followed by wildlife (noncattle) consumers. The livestock demand is computed based upon growing steers or their equivalent, the number of animals, average weight, and their physical condition.

Demand for herbage is partitioned over the herbage supply categories. The quantity demanded from the supply is derived from plant species preference and site preference data inputs. Each cell of the herbage demand matrix is compared with the corresponding cell of the supply matrix. If no cell of the demand matrix exceeds the corresponding cell in the supply matrix, animal demand is met. If any of the herbage supply matrix cells are less than demand, cattle demand is recalculated and the computer-simulated consumers search for herbage from less desirable plant species and from less desirable grazing sites. The search by the computer grazer to satisfy dietary demand continues until the demand is met or available vegetation is exhausted. The realized diet and its nitrogen content are used to compute digestible dry matter intake. Digestible dry matter intake provides for the calculation of animal response in a modified version of the model of Sanders and Cartwright (1979). Excretal nitrogen return to the rangeland is determined from the amount of nitrogen consumed which is not digested and urinary nitrogen excretion.

WILDLIFE CONSUMERS (Vavra and Raleigh 1983)

The wildlife subcomponent allows for up to 10 noncattle consumers. Species or various sex and age categories are possible. Food habits, daily forage intake, grazing time frame, site preference, and population size are user inputs.

Changes in wildlife population size and/or herd composition due to predation, hunting, drought, or winterkill are not expressed in the subcomponent. At this time, the user may change wildlife numbers only by stopping the model run at the expected time of population change and inputting new population and/or herd composition data and beginning a new run.

Wildlife consumers are present on most western rangelands and comprise a significant force in forage removal. Users involved with forage allocation on public lands must, by law provide, through the multiple use concept, forage for wildlife. The model in its present form does make this accommodation.

INSECT CONSUMERS (Onsager and Hewitt 1983)

SPUR can estimate the seasonal distribution and total amount of forage destruction by typical populations of mixed grasshopper species. Required inputs are the average stage of grasshopper development and the average density per square yard. The former can be estimated from a sample of about 100 grasshoppers which is sorted into the different developmental stages (the five successive nymphal instars plus the adult stage). SPUR then converts average development to average age, converts average density to average number of hatchlings per square yard, estimates total forage destruction to date, and estimates total potential forage destruction for the season. This information allows a manager to rationally assess various options, such as adjustment of stocking rates, overgrazing, or grasshopper control measures.

ECONOMIC COMPONENT (Godfrey and Torell 1983)

The economic component was built primarily on the output of the animal component. The evaluation of all economic benefits is based on the response of animal gains and increased herd size from various alternative grazing and improvement strategies that may be considered. Necessary inputs for the economic component which must be provided by the user include the following: the value of the animal gains in dollars per hundred weight, the applicable discount/interest rate to be used for discounting, and the fee and nonfee costs of forage on a per animal, acre, or animal unit month (AUM) basis. The primary outputs include the following: animal gains per day and per AUM of forage consumed, the value of these gains, and the costs of using the grazing management unit. These outputs are summarized monthly. These outputs are then discounted to derive the present value of the net benefits (value of animal gains less the fee and nonfee costs of grazing the grazing unit) over the planning horizon. The internal rate of return and benefit/cost ratio for the project being considered may also be calculated.

PRESENT STATUS AND FUTURE DEVELOPMENT

To enhance the orderly development of SPUR, three developmental phases have been defined:

Phase 1. The objective of phase 1 is a SPUR model that can simulate the responses of a shortgrass prairie ecosystem in terms of aboveground plant production, cattle weight gains, soil water, and runoff. Phase 1 includes sensitivity analyses, documentation, and preparation of user guides.

Phase 2. The objective of phase 2 is to extend the application of SPUR to other major rangeland ecosystems, validate the plant-animal interface, and include the following features which are not currently part of the model.

1. Cow-calf capabilities.
2. Flexible grazing systems.
3. Plant- and animal-hydrology feedbacks.
4. Internal parameterization of the plant component.

Currently the model considers only steers or steer equivalents; grazing seasons are fixed and cannot be changed during a simulation; and SCS CN's and MUSLE factors are also fixed as initial conditions and do not change during a simulation to reflect simulated changes in vegetation or animal impacts.

Phase 3. The objective of phase 3 is to enhance technology transfer and continue model improvement and refinement.

Data from the International Biological Program Grassland Study at the Pawnee site in Colorado, is being used for phase 1. Sensitivity analyses and documentation are underway and will be completed, along with user guides, in 1984. At this point, SPUR will be available for use by other scientists and for some limited application in resource management.

Under phase 2, the major effort will be the quantification of the plant component parameters for major rangeland forge species or species groups; the testing of the plant-animal interface, particularly the efficacy of the preference vectors; and the development of plant- and animal-hydrology feedbacks. The latter is necessary to simulate grazing and climatic impacts of runoff and erosion. The internal parameterization of the plant component is also an important feature of phase 3 and will greatly reduce the number of user inputs making SPUR more user-friendly.

While major emphasis is currently on phase 1, activities under phase 2 and phase 3 are ongoing. Modeling of crested wheatgrass pasture systems is currently underway and demonstration runs on native range pastures are being conducted for management agencies.

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APPENDIX

PARAMETERS AND VARIABLES FOR THE BASIN SCALE VERSION OF SPUR

Number of channels (max=9)	Watershed area (mi^2)
Number of Fields (max=23)	Area of each field (acre)
Number of plant species (max=7)	Initial soil moisture

CLIMATE COMPONENT

Input Variables

Daily precipitation (in)
Maximum daily temperature (F)
Minimum daily temperature (F)
Daily solar radiation (ly)
Daily wind run (mi)

Parameters

(Required to stochastically generate all or part of the above climate parameters)

Probability of wet day given a wet day for each month of year (tabular)
Probability of wet day given a dry day for each month of year (tabular)
Scale parameter for gamma distribution that generates daily precipitation amount (required for each month of the year) (tabular)
Shape parameter for gamma distribution that generates daily precipitation amount (required for each month of the year) (tabular)
Fourier coefficients of max temp on dry days (total=4) (map)
Fourier coefficient of max temp on wet days (map)
Fourier coefficients of min temp (total=4) (map)
Fourier coefficients of radiation on dry days (total=2) (map)
Fourier coefficient of radiation on wet days (map)
Mean wind velocity (climatic atlas)
Standard deviation of wind velocity (climatic atlas)
Mean wind velocity for month (total=12) (climatic atlas)
Latitude (degrees)
Elevation (ft)

HYDROLOGY COMPONENT - WATER BALANCE

(Parameters are required for each site unless otherwise noted)

Input variables

Initial snow water equivalent (mm) (by site)

State variables

Runoff
Upland sediment yield (T) (by site)
Peakflow rate (site and channel)
Soil moisture (by site)
Soil evaporation (by site)
Plant transpiration (by site)
Snow water equivalent (by site)
Snow areal cover (by site)
Snowmelt (by site)
Deep percolation (by site)
Subsurface return flow (by site)
Watershed sediment yield (T)

Parameters

Number of soil layers (max=8) (soil survey)
Condition I curve number (SCS Hydrology Handbook)
Universal soil loss equation (USLE) K factor (USDA Handbook 537)
USLE slope-length (SL) factor (USDA Handbook 537)
USLE practice (P) factor (USDA Handbook 537)
USLE cover (C) factor (USDA Handbook 537)
Rooting depth of plants (in) (soil survey)
Soil evaporation parameter (CREAMS Handbook)
Return flow time (days)
Crack factor (decimal)
Aspect of site (degrees) (topographic map)
Slope of site (ft/ft) (topographic map)
Soil porosity/soil layer (in/in) (soil survey or tabular values for texture class)
1/3 bar water content/soil layer (in/in) (soil survey or tabular values for texture class)
15 bar water content/soil layer (in/in) (soil survey or tabular values for textures class)
Saturated hydraulic conductivity/soil layer (in/hr) (soil survey or tabular values for texture class)
Depth of each layer (in) (soil survey)

HYDROLOGY - SNOW ACCUMULATION AND MELT

Parameters

One set for each site (Range of parameter values are given in Anderson, E.A. 1973. NOAA Tech. Mem. NWS HYDRO-17)
Snow correction factor to adjust gage for catch differences
Maximum melt factor assumed to occur on June 21 (mm/C hr)
Minimum melt factor assumed to occur on Dec 21 (mm/C hr)
Average wind function during rain-on-snow periods (mm/mb hr)

Parameters (cont'd)

Mean areal water equivalent above which there is 100% snow cover (mm)
Areal snow cover depletion curve type (ranges from 1.0 to 5.0)
Maximum negative melt factor (mm/C)
Weight applied to proceeding period's temp in order (decimal) to calculate current snowpack temperature
Base temp for snowmelt during nonrain periods (C)
Temp which delineates rain from snow (C)
Percent liquid water holding capacity of solid portion of snowpack
Daily ground melt (mm/day)
Areal depletion curve

HYDROLOGY - CHANNEL FLOW

Parameters for each channel

Channel length (mi)
Channel width (ft)
Channel hydraulic conductivity (in/hr)
Channel slope (mi/mi)
Total channel roughness (sec/ft**1/3)
Channel wall roughness (sec/ft**1/3)
Median particle diameter in bed, d_{50} (mm)
Fraction of silt and clay (decimal)
Suspended sediment transport coefficient (sec/ft)
Particle size class diameter (mm) (max=10)
Particle size class fraction (decimal) (same as diameter class)

(The following are required if ponds are included)

Full pond area (ac)
Full pond volume (ac-ft)
Initial pond volume (ac-ft)
Saturated hydraulic conductivity of pond bottom (in/hr)

PLANT COMPONENT

Input variables

(Initial conditions site specific, nonspecies specific)

Inorganic nitrogen content of soil (g/m**2)
Dead root phytomass (g/m**2)
Litter biomass (g/m**2)
Organic matter biomass (g/m**2)

(Site and species specific)

(The initialization of the nitrogen state variables is based on the phytomass values.)

Standing live phytomass for the ith species (g/m**2)
Live root phytomass for the ith species (g/m**2)
Propagule phytomass for the ith species (g/m**2)
Standing dead phytomass for the ith species (g/m**2)

State variables (by site) (all value g/m**2)

Aboveground live phytomass (by species)
Aboveground dead phytomass (by species)
Propagule phytomass (by species)
Live root phytomass (by species)
Dead root phytomass
Litter phytomass
Organic matter (soil)
Soil inorganic nitrogen
Nitrogen content of aboveground live phytomass (by species)
Nitrogen content of aboveground dead phytomass (by species)
Nitrogen content of propagule phytomass (by species)
Nitrogen content of live root phytomass (by species)
Nitrogen content of dead roots
Nitrogen content of litter
Nitrogen content of organic matter (soil)

Parameters

(The plant parameters are divided into species dependent parameters and pasture dependent parameters.)

Species specific parameters:

Theoretical maximum net photosynthetic rate
Light use efficiency coefficient
Maximum temperature for positive plant activity (C)
Optimum temperature for positive plant activity (C)
Minimum temperature for positive plant activity (C)
Water potential at which photosynthetic activity is one half maximum (bars)
Drought tolerance coefficient
Proportion of photosynthate translocated to roots after senescence begins
Root to shoot ratio
Wind tolerance coefficient (km)
Precipitation tolerance coefficient (cm)
Proportion of phytomass susceptible to trampling
Stocking rate tolerance (standing dead)
Stocking rate tolerance (green shoots)
Proportion of green shoots susceptible to death
Phytomass to leaf area conversion factor (m**2/g)
Proportion of photosynthate translocated to propagules after flower initiation
Proportion of root phytomass translocated to shoots
Germination proportion
Dark respiration rate
Respiration temperature control coefficient (C)
Respiration water control coefficient (bars)
Seed mortality proportion
Root respiration proportion
Root mortality proportion
Maximum nitrogen uptake rate
Nitrogen use efficiency coefficient (m/g)

Critical species dependent parameters

Leaf area
Frost kill temperature
Ten day mean temp. for translocation from roots to shoots (TRS)
Water potential for TRS
Water potential for seed germination
Day seed production begins
Day senescence begins
Day senescence ends

Pasture specific parameters

Portion of dead roots susceptible to decomposition
Portion of litter susceptible to decomposition
Portion of organic matter susceptible to decomposition
Moisture tolerance of denitrification
Water potential at which decomposition activity is one half maximum (bars)
Drought tolerance coefficient for decomposition

ANIMAL COMPONENT

(There are two forage classes for each plant species -- live and dead.)

Input variables

Number of wildlife species (max 10)
Population size for each wildlife species (count)
Number of grazing steers (count)

State variables

Steer weight (kg)
Steer forage demand by site and plant species class (kg)
Steer forage consumed by site and plant species class (kg)
Digestibility of forage (decimal)
Forage consumed by wildlife by site and plant species class (kg)
Carbon excreted by livestock by site (kg)
Nitrogen excreted by livestock by site (kg)

Parameters

For the average steer:

A. Time at turnout (days)
B. Time at roundup (days)
C. Age at turnout (days)
D. Weight at turnout (kg)

Supplement for average steer (if required):

A. Amount of supplement (kg/head/day)
B. Time of initial supplemental feeding (days)
C. Time of last supplemental feeding (days)
D. Digestibility of the Supplement

Vector preference for forage classes (1, decimal)
Vector of physical limitation on use of forage classes (decimal)
Vector of preference for locations (1, decimal)

Vector of physical limitations on use of locations (decimal) by wildlife species:

A. Vector for location preferences (1, decimal)
B. Forage preference vector (1, decimal)
C. Time entering the system (days)
D. Time exiting the system (days)
E. Daily dry matter intake for each wildlife species (kg)

Asymtotic mature size of a cow of the same herd (kg)

SIMULATION OF PRODUCTION AND UTILIZATION OF RANGELAND (SPUR) MODEL - DISCUSSION BY SCS

Donald T. Pendleton[1]

I have followed the SPUR modeling effort by ARS scientists closely since its inception. Dr. Wight has kept us well informed. We in SCS who work with range are eagerly awaiting the maturation of the SPUR model. Some SCS employees from the West National Technical Center and the Idaho State Office have worked with Dr. Wight in testing SPUR on selected ranches. We appreciate this opportunity.

In range ecosystems, models must integrate data regarding the plant sciences, animal sciences and livestock husbandry, and climate. SPUR does this. We are particularly interested in the pasture scale part of SPUR for use in conservation planning with livestock operators. We believe it will be able to answer many "what if" questions that arise at the ranch or allotment planning level. The economics component looks attractive also (Wight 1983). Over the past several years SCS has put a great deal of effort and considerable funds into several simple economics models, such as Computer Optimization Planning (COPLAN) and programs for hand-held calculators. We need to discuss these to see if any of them could contribute to SPUR and to avoid duplication of effort.

WIND EROSION EQUATION (WEQ)

Dr. Cole's presentation was concerned with cultivated soils, or what he called agricultural fields. I would invite my colleagues, national agronomist Gerald Darby and national sedimentation geologist Bill Mildner, to ask questions or provide comments regarding the WEQ and tilled agriculture. My concern, however, is with areas of permanent perennial vegetation-grasslands and shrublands. We are familiar with the WEQ work of Dr. Lyles at Manhattan and of ARS scientists at Big Spring, Texas. We appreciate the efforts of these scientists.

There is a tendency by some to think of the Great Plains as the sole province of wind erosion. But the Great Plains does not have a monopoly on this destructive process. Wind erosion is common in the sagebrush and juniper of the Great Basin, the mesquite and shinoak of New Mexico and West Texas, and several other shrub ecosystems. Herein lies a problem: the WEQ requires that all vegetation cover (dry weight/acre) be expressed as a small grain equivalent. Range conservationist Donald Fulton of the West National Technical center has attempted to make this conversion for several of the major grasses and shrubs common in the Western States. But can you imagine trying to convert big sagebrush and Utah juniper into small grain equivalent? If the WEQ is to encompass situations like these, then scientists must tackle the problem head on, not through small grain equivalent. Thus, we plead for the use of canopy cover, foliar cover, basal area, or some other measure common to grasses, forbs, and shrubs directly in the equation.

We are pleased that SCS soil conservationist Bill Hance has been assigned to work with Dr. Lyles and Dr. Cole at Manhattan. We hope an improved WEQ for use on rangeland will be forthcoming from that joint effort.

I would like to echo the words of George Comer and other speakers in a previous session. Key words and phrases concerning models that I heard and like include (a) operational models, (b) client and constituency orientation, (c) simplification and generalization, and (d) verification and validation.

UNIVERSAL SOIL LOSS EQUATION (USLE)

We must have verification or modification of the factors of USLE, or other erosion prediction equations, for use on arid and semiarid grasslands and shrublands. Our credibility is on the line. For example, many of you are aware of the running dialogue between Drs. Trieste and Gifford (1980) on the one hand, and George Foster, et al (1981) on the other hand, concerning the utility of USLE on rangeland in the Journal of Range Management. Much of the misunderstanding was doubtless the result of misuse of the equation. Nevertheless, there is a strong feeling among range scientists that the equation needs a great deal of fine tuning to be acceptably accurate and useful on rangeland. Erosion prediction equations have some very significant ramifications for range management and range programs. For example, USLE is a basic tool in the selection and designation of range targeted areas as discussed in the National Conservation Program. The equation is also used as the basis for differential cost sharing by ASCS in some trial areas.

Some specific USLE factors that we feel need refinement are as follows:

C factor.-- Most range scientists feel that surface stones and desert pavement can best be addressed in the C factor.

R factor.-- The effects of elevation on precipitation in short distances is problematic in the West. So also is the frequency distribution of erosion-producing events, especially in the Southwest.

K factor.-- Results of research by some state agricultural experiment stations do not always agree with published K factors. In California,

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for example, 5 years of research indicated a K factor of 0.03 for Auburn soils, calculated from measurements. These same soils would have a factor of 0.22 to 0.30 as estimated by using Agriculture Handbook 537. The difference, researchers felt, is due to the presence of iron oxides, which reduce erodibility but are not considered in the K factor in Handbook 537.

LS factor.-- The subtle relief patterns under perennial vegetation are difficult to determine, and better guidelines are needed regarding slope length.

Until these refinements are made, we insist that the tried and proven concept of range condition and trend is a more accurate and more timely indicator of plant/soil problems and should be used in lieu of soil erosion.

GULLY EROSION

Gully erosion is a significant part of total erosion on rangeland, but current methods for quantifying it are inadequate. Can models be developed to simplify and to increase the accuracy of soil loss in gullies? We ask for your help in this area.

INFILTROMETER/RAINFALL SIMULATOR DATA

Almost all rangeland erosion and sedimentation studies use infiltrometers or rainfall simulators on small plots on an event or per-storm basis. Can modeling provide a procedure for using point or small plot data to predict average annual soil loss on a pasture or watershed basis? Or would we be better off to address erosion on a single event or per storm basis?

BASIC DATA FOR MODELS

We must be cautious of the temptation to bridge by modeling too many or too wide gaps in data. In fact, part of the usefulness of models is that they help identify additional needs for basic data. SCS has several ongoing and embryonic projects which may be useful in building range models. These include (a) COPLAN, (b) programs for hand-held calculators as an aid for conservation planning, (c) a national soil/range team, and (d) a range data system. I would be glad to provide details about these activities.

EROSION SYNDROME

Dr. Al Grable aptly said yesterday that the relative priority of soil and water conservation has never been higher or more visible. It is only natural and correct that we capitalize on that visibility. Erosion and erosion reduction are buzzwords today. In fact, I fear we are in an "erosion syndrome." Let me hasten to explain that I do not belittle or condone erosion. It is a national menace, a luxury we cannot afford. But the emphasis on erosion as the sole criterion of a resource problem and the primary justification for increased funds and people may be creating an undesirable mental attitude among conservationists. Recently several SCS employees have pointed out "good erosion" to me. Ostensibly, by good erosion they mean erosion that is bad enough or visible enough to justify an application for additional technical and financial assistance as a targeted area.

The point I want to make is that on permanent perennial vegetation (range, pasture, or forest), the identification of unacceptable soil erosion as a problem is a post mortem evaluation. The care and management of the vegetation must be our first line of defense against erosion. Any astute range conservationist, agronomist, or biologist by observing the vegetation, can foresee an unacceptable rate of soil erosion long before it occurs and can suggest alternative management strategies to avoid it. Obviously, where the plant community has deteriorated to a condition that permits excessive erosion, we should "fix the broken part," providing it can be restored. But preventive maintenance, through forage and animal management, should be the watchword on grasslands and shrublands so that erosion does not become a problem.

Let me leave one further thought with you. Webster's Dictionary defines erosion as "progressive impairment or destruction, as if by eating or wearing away." In the broadest sense of the word, then, erosion includes degradation of the <u>plant resource</u> as well as the <u>soil resource</u>. I suggest we incorporate this idea into our dialogue concerning erosion.

T VALUES

The National Conservation Program identifies nondegradation of soil, water, and related resources as its primary objective. Erosion reduction or control is a means to achieve that objective. Most range scientists and conservationists agree that average annual erosion rates of 3, 4, or 5 tons per/acre result in resource degradation in range ecosystems. Range scientists also feel that soil losses at these rates will not "permit a high level of crop production to be sustained economically and indefinitely" on rangeland (Wischmeier and Smith 1978). Therefore, these rates are not tolerable on fragile and unforgiving ranges, where organic matter is low and soil regeneration slow, where soil amendments and tillage are not ordinarily used to hasten the soil building process or to correct past erosion. The loss of as little as 1/2 ton of soil per year may permanently impair the ability of that soil to support native vegetation. To say that 3, 4, or 5 tons per acre is tolerable is to condone a level of management that is detrimental to the plant community.

With these thoughts in mind, we arbitrarily but objectively established 2 tons as the maximum T

value for rangeland in the 1980 RCA Appraisal. We acknowledge that we have little or no scientific basis for this figure. But if we are in error, we prefer to err on the conservative side. We have talked with several imminent range hydrologists concerning T values for rangeland. Among them are Ken Renard and Cliff Johnson of ARS, Will Blackburn and Robert Knight of Texas A&M University, Gerald Gifford of Utah State University, Karl Wood of New Mexico State University, and John Buckhouse of Oregon State University. In general, they agree that the higher T values are unacceptable on rangeland. On soils with existing T values of 1 ton/acre, we propose that the lower rate apply. One problem that we still must resolve is how to handle steep soils in arid climates that support only sparse vegetation and that have natural or geologic erosion rates in excess of 3 to 5 tons per acre. We plan to prepare a supplement to the SCS "National Range Handbook" regarding T values of rangeland, and we solicit your best thoughts on the subject.

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WIND EROSION MODELING

George W. Cole[1]

INTRODUCTION

As the title implies but does not make clear, the subject of this paper is the mathematical modeling at the USDA, ARS, Wind Erosion Research Unit, Manhattan, Ks. The modeling is concerned primarily with the prediction of soil loss from agricultural fields.

We shall review briefly the wind erosion equation (model) and its modifications and from this show how our present philosophy of modeling evolved and how we expect the modeling to develop in the future. For completeness we shall also mention two other models, one that simulates the airflow around porous windbreaks, and the other, surface soil moisture.

THE WIND EROSION EQUATION AND ITS MODIFICATIONS

Although earlier versions of the wind erosion equation were published (Chepil and Woodruff 1954, 1959; Chepil 1959, 1960; Chepil et al. 1962; Chepil 1962), the base line equation, which we refer to as the wind erosion equation, is documented in Woodruff and Siddoway (1965). Some insights into the development of the equation are presented by Cole et al. (1982).

The functional form, as given by Woodruff and Siddoway (1965), is

$$E = f_1(I, K, C, L, V) \tag{1}$$

where the factors are as follows: E, the potential average annual soil loss; I, erodibility; K, surface roughness; C, climatic factor; L, equivalent field length; and V, the vegetative factor. (See Woodruff and Siddoway (1965) for a detailed description of the factors.)

A more mathematically rigorous form, as given by Cole (1982), is

$$E = f_2(V, f_3(IK, IKC, L)). \tag{2}$$

This form can be easily verified by observing how E is computed in Woodruff and Siddoway (1965).

Equation 2 represents the base line equation for the models to be discussed since they are really minor variations on how to compute either the C or L factors or how to subdivide E. In fact, the underlying theme for these changes is related to the unconscious feeling that E should be a flux and that the factors such as I, K, C, and L should vary with time. We shall return to this later when we discuss the direction of the present modeling effort; but first, let us summarize quickly the modifications made on equation 2.

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Chepil recognized the fact that all of the factors he defined could be considered to change with time and, indeed, he coped with the wind angle fluctuations (Chepil et al. 1964) by defining a prevailing wind direction angle. This angle is determined by constructing a wind erosion rose, which is a set of 16 normalized vectors whose magnitudes are proportional to the time-weighted sum of the average velocity cubed. By selecting the maximum vector that would fit within the rose, Chepil assigned the angle of this maximum vector as the angle A. He utilized this angle to compute a single value:

$$L = w \sec A \qquad 0° < A < 85° \tag{3}$$

where w is the short side of the rectangular field.

Skidmore (1965) and Skidmore and Woodruff (1968) made two modifications to Chepil's method of determining L. First, they determined the prevailing wind direction by decomposing the 16 normalized vectors into tangential and normal components about an arbitrary coordinate system. The sum of the magnitudes of the normal components divided by the sum of the magnitudes of the tangential components is called the preponderance function and it was maximized by rotating this new coordinate system. The resultant angle between the x axis and east was considered the prevailing wind direction.

Skidmore (1965) did not use this angle to substitute into equation 3 to determine a single L, but instead used his prevailing wind direction angle in conjunction with his field angle and 16 vector angles to determine 16 field lengths by application of equation 3. To each length he assigned a probability, based on the relative energy computed for each L and, consequently, developed a cumulative probability density function. From this he selected a median value of L, which was designated as "the equivalent field width." This latter width was used as the L in equation 2.

A proposal to modify C to a monthly factor was put forth in Woodruff and Armbrust (1968) and Skidmore and Woodruff (1968), but it does not appear to have been used extensively.

Perhaps the most significant modification in the use of equation 2 is the partitioning of E with time, as proposed by Bondy et al. (1980). They used an erosive wind energy factor to subdivide E into periods of a fraction of a crop rotation cycle while utilizing the period values for K, L, and V. Here we note the first attempt at viewing E as a point flux rather than as an average flux and hence treating the independent variables as functions of time. It is interesting to note that Chepil et al. (1964) and Bondy et al. (1980) both used a form of an energy factor to apportion yearly soil loss. Chepil et al. (1964) apportioned within an arc and Bondy et al. (1980) within a time interval.

A computer program for the solution of the wind erosion equation (WEROS), which incorporates the preponderance concept, has been programmed in Fortran (Skidmore et al. 1970). It allows for the solution of any single variable given all of the others. With this feature, one can conceivably determine an optimum control strategy.

Another modification to the wind erosion equation was made to allow its incorporation into the EPIC (Erosion Productivity Impact Calculator) model. This consisted primarily of incorporating the erosive wind energy concept (Bondy et al. 1980) with the subroutines of WEROS (Skidmore et al. 1970), which were concerned with the solution of equation 2. The time step of 1 day required the computation of the erosive wind energy factor for 1 day. In addition, a method of handling multiple simultaneous crops was developed. For the details, see Cole et al. (1982).

OTHER WIND EROSION MODELS

Two other models have been developed. The first (Hagen et al. 1981) simulates the airflow near a porous wind barrier. This model solves five partial differential equations in order to simulate two-dimensional flow normal to a narrow windbreak. The equations are those of conservation of horizontal and vertical momentums, mass, turbulence energy, and the dissipation rate of turbulence energy. The method of solution utilizes finite-difference techniques.

The second model (Skidmore 1983, personal communication), which is still in the development stage, simulates the effect of soil moisture on the soil flow rate per unit width. This effect is represented as a cohesive stress due to moisture, which reduces the wind shear stress. The cohesive stress is determined from climatic variables--for example, air velocity, humidity, temperature, and net solar radiation--and the hydraulic properties of the soil. Preliminary validation results suggest that the model output, that is, the climatic erosivity factor, is related linearly to a calculated suspension flux.

AN ANALYSIS OF WIND EROSION EQUATION LIMITATIONS

From the previous historical review of the wind erosion equation, it should be apparent that any changes made to the base line equation, that is, equation 2, were due to the difficulty of determining single values for factors such as I, L, V, and K. This difficulty appears to have arisen because of the ambiguous methods suggested for their determination; e.g., Woodruff and Siddoway (1965) stated that "The equation actually evaluates the erodibility of a field having certain L, K, and V values in terms of what it would have been during the severe soil blowing time." In Chepil et al. (1964) we note that the prevailing wind direction used to compute L (equation 3) is based upon long-term wind distribution data, which implies more than the severe blowing season. Obviously, we have a contradiction.

If one has difficulty in selecting the factors for equation 2, then his confidence in the prediction of values of E may be quite low, especially when he visualizes that these factors would change during the yearly cycle. This feeling apparently lead to the modification previously discussed.

Reviewing these changes indicates that there was a prevalent feeling that, if the factors which affect E could be described as functions of time rather than as a single value, then the computed value of E would be more accurate. Furthermore, since the loss of soil tends to be higher during certain months of the year, a knowledge of the magnitude of the erosion process during this shorter time interval would be more useful for control practices.

This reasoning then leads to the following questions: What is E for a period shorter than a year? Is E a good measure for short periods? What is E? What is the measure of soil erosion?

To answer these questions, and many more that they engender, an analyses of the significance of E as a measure of the soil erosion process was performed. The results of this as yet unpublished study can be summarized by the following two equations:

$$E = \text{Expt.}(\langle\langle f\rangle_A\rangle_T) \tag{4}$$

where

$$\langle\langle f\rangle_A\rangle_T \triangleq \frac{1}{AT}\int_T\int_A f \, da \, dt = \frac{m}{AT}. \tag{5}$$

Equation 4 indicates that E is the statistical average (or mean) of the arithmetic average of the normal component of the soil loss flux vector, f (a function of time and space), where the arithmetic average is over the area A and time interval T of 1 year. It is important to distinguish between the two types of averages so that it can be made clear what is implied by the generally accepted definition for E; that is, Woodruff and Siddoway (1965) defined E as "the potential average annual soil loss in tons per acre per annum."

From equation 5 we see that the arithmetic average of f is also equal to the normalization of the mass loss, m, by the area and time interval. This average is the annual soil loss of the above E definition; that is,

$$\text{annual soil loss} = m/(A\cdot T); \quad T = 1 \text{ yr.} \tag{6}$$

The potential average represents the statistical average, shown in equation 4.

Equation 5 emphasizes three important points. First, that the average flux is dependent on time and space intervals and not on points within the interval, whereas f is a function of points of time and space within the intervals. This leads immediately to the observation that to develop an E equation for any time interval, the flux function is generally required. Furthermore, since

$$f = f(U(t), K(x,y,t), M(t), \ldots) \tag{7}$$

(where U is the windspeed, K some function of roughness, M a function of soil moisture, and ... implies other unspecified variables), it is at this level of definition and not at the E level that it is legitimate to apply time-varying functions to improve the accuracy of predicting E.

The third observation to be made from equation 5 is that the area and time intervals only enter into the computation of <<f>> as limits of integration and as a denominator. They are not computed. They must be specified. It is the soil flux and hence the soil lost (m) during the period T that is computed.

The importance of this is that any measure of the soil loss process depends on the soil loss mass. This further suggests that the phrase "soil loss" when used as a noun be reserved for m and when used as a process, while always sufficiently quantified by <<f>>, may be measured for special cases in other ways. For example, if one were comparing the soil loss processes for the same field and the same interval of time for two different soil conservation strategies, then a predicted m would be a necessary and sufficient measure.

TASK DEFINITION

From the above, we now see that improvement of prediction of any measure of the soil loss process is predicted upon three major tasks which are implied by equations 4 and 5: (1) the functional form of f, (2) description of the factors upon which f depends, both in time and space, and (3) methods for integration of f in time and space.

The first two are necessary for any measure of the erosion process and all three for the development of an improved wind erosion equation.

Another way to subdivide the modeling tasks is by relating the three major tasks to the concept of soil loss tolerance (τ) and a crop productivity tolerance (Π). In a sense, the soil loss tolerance is a limit placed on one part of the plant-soil system whereas a productivity tolerance is a restriction on the crop, the most significant output of the system.

If one utilizes τ as a limit, then

$$E \leq \tau \tag{8}$$

and all three of the tasks are necessary. However, if one adopts crop productivity (P) as a criterion, then

$$\Pi \leq P \tag{9}$$

where P is analogous to E in that it is an expected value of an average crop flux (kg/(ha·yr)), then only the first two tasks are required. It is worth noting that the disappearance of the third task is only apparent, since for a soil flux function to be of any use, it must tie into a comprehensive model, that is, EPIC, where the integration must be performed. The benefit of the productivity criterion is the lack of a need for a constraint on f since the constraint has been moved to a higher level, such as, crop productivity.

PRESENT MODELING EFFORTS

We have embarked on a modeling program to meet the τ criterion, that is, we consider this the immediate goal in that it is limited to the process of soil erosion and, with the exception of the integration task, all tasks also benefit the Π approach.

The development of the flux equation is envisioned at present as being quite experimentally oriented. Much of the early wind erosion research was devoted to finding q, the first integral of f with distance downwind, for various values of the surface conditions:

$$q = \int f \, dR. \tag{10}$$

The problem of time and space integration had not been satisfactorily accomplished and does not, at least conceptually, depend on experimentation except for validation. It depends more on establishing the model of a field in terms of f or q, establishing a reference coordinate system, and then determining how to perform the integration.

Spatial Integration

The task of integration has been selected as the initial research effort, and the results of the spatial integration was reported (Cole 1984).

The resulting equation, which allows calculation of the mass flow rate of soil loss ($\dot{m}$), given the appropriate q function, for any convex field is

$$\dot{m} = \oint_C q(r(R(u),u),h,J)\, du. \tag{11}$$

C is the path denoted by the perimeter of the field, u is the crosswind coordinate, h is the height of the saltation layer, r and R are downwind coordinates, and J is the set of surface properties of the field which may change with time, for example, the windspeed. Now the R,u coordinate system is relative to the wind vector, and when $\dot{m}$ is expressed in terms of a line integral around the path C (which is more amenable to machine integration), equation 11, due to a coordinate transformation, becomes

$$\dot{m} = -\oint_C q\{r[R(u(s,\beta)),\ u(s,\beta)],\ h,J\} \cdot \{\frac{dy}{ds}\cos\beta - \frac{dx}{ds}\sin\beta\}\, ds \tag{12}$$

The new variables are s, the distance along C; $\beta(t)$, a wind angle function; and x(s),y(s), the position coordinates of s relative to the x,y reference frame which is fixed to the earth. Via equation 12, one can calculate $\dot{m}$ for any convex field. Cole (1984) has developed from equation 12 the model for a homogeneous rectangular field with a nonerodible boundary. The equation for a circular field also has been developed.

As an outgrowth of this work, we are trying presently to apply a similar concept to equation 2, the wind erosion equation, to reduce the number of factors required to compute E. As part of the EPIC submodel validation, a modification of WEROS (Skidmore et al. 1976) was used to compute soil loss by periods (Bondy et al. 1980). By utilizing this modification and considering a large field to be

subdividable into narrow subfields (trapezoids and triangles, or rectangles) for any wind angle, β, then the E for the field is computed as the weighted sum of the individual E's, where the weight factor is the percentage of the total area.

The advantage of this scheme is that L for the field is no longer required. Furthermore, since we now compute an E for the field for each of 16 β's, we also now compute erosive wind energy factors directly from wind distribution data, as a function of crop stage period and wind angle, rather than precomputing and entering as was done previously (Bondy et al. 1980).

For those familiar with the concept of preponderance (Skidmore and Woodruff 1968), we have eliminated the need for it by transferring the energy weighting scheme associated with preponderance into the computed erosive wind energy factors. This obviously increases the number of calculations to the point where they must be done on a computer. This model is still in the development stage.

Time Integration

In order to evaluate equations 4 and/or 5, we must make further assumptions about the flux function, that is, whether or not we consider it to be deterministic in time in the statistical sense. If considered deterministic, then we can pass on and consider its independent variables (equation 7) and pose the same questions. At present, since the functional form of f or q is in the future, we shall assume the function to be deterministic.

The question for the independent variables is not answered so clearly since some of the variables can be considered stochastic, such as the wind, and others deterministic. However, if one is dealing with a postdiction situation, even the wind can be considered determined. Consequently, when all variables are deterministic, the time integration problem is conceptually trivial and depends strictly upon an adequately sampled set of functions and sufficient storage space in computer memory. The solution to equation 4 is then equation 5 since the arithmetic average is not a random function of time.

For the prediction problem, which is what is implied when one is interested in using the wind erosion equation, it appears that unless one knows what the future functional form of all the variables will be, he will have to be satisfied with a statistical approach which treats some of the variables as random and predicts only a mean value.

The advantage of this approach is that we do not need long strings of data representing such functions as the future wind. It allows us to replace the time integration of f with the integration implied in the definition of the statistical mean for the random variables and a finite time integration for the deterministic variables; that is, from equation 4 we have

$$E = \langle \text{Expt.}(\langle f \rangle_A) \rangle_T \qquad (13)$$

where

$$\text{Expt.}(\langle f \rangle_A) = \int_{-\infty}^{+\infty}\int \langle f(U,\beta,D(t)) \rangle_A \cdot p(U,\beta)\, dU\, d\beta \qquad (14)$$

and D(t) represents the set of all deterministic variables. A $p(U,\beta)$ is the joint probability density function for the random functions of the wind vector, here assumed as the only random function. Other random functions also could be included as needed.

Now the time interval implied by T in equation 13 would be the period for which D(t) would repeat itself. The selection of T as this period is justified, since the time average implied by equation 13 would repeat itself with period T and with sufficient time would approach a constant value, so any further integration would be useless. The period of T in equations 4 and 5 was assumed to be 1 year; however, here its more general meaning is apparent. A typical prediction might have a T equal to the crop rotation period.

From this reasoning we see that to solve equation 13, we must replace the long-term time integration implied in equation 4 with, say, a 3- or 4-year period plus the integration of equation 14 for each time step of the interval T.

Further work is needed to determine how to handle other stochastic variables of f, such as soil moisture and its relationship to precipitation and the availability of precipitation probability density functions.

FUTURE MODELING EFFORTS

This effort can be subdivided into two parts, both of which are continuations of the tasks outlined previously.

The first is the development of the software and selection of appropriate hardware for the solution of equations 5 and/or 13. The primary tasks would be time and spatial integration and graphical input-output capability. The latter capability would allow for inputing field boundaries, nonerodible boundaries, vegetative patterns, and so forth, as well as time functions from a digital tablet. This capability would thus avoid tedious keyboard entry of certain data sets. Also, a graphical display of these time and spatial functions will be required for verification of the data entered.

Further improvements might include simplified data retrieval capability for the frequency distribution of the wind and precipitation data.

The second part of this effort, and most likely the most difficult, will be the determination of the functional form of f, that is, equation 7, or more realistically, q, its downwind integral. It is not clear at this point how this functional form will be determined; however, a polynominal fit of some type may be required similar to the Group Method of Data Handling of Ivakhnenko (Tamura and Halfon 1980).

A further logical extension of equation 7 would be the determination of the distribution of f by aggregate size. This extension comes about as a result of visualizing the wind erosion process as affecting the soil-plant system by both selective and total soil loss (Lyles et al. 1983).

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SIMULATING SOIL-WATER HYDROLOGY[1]

Keith E. Saxton[2]

INTRODUCTION

Simulation models of soil water have a broad range of detail and complexities. The amount of input required and accuracy of results is closely related to this spectrum. Several simulation models have been developed that provide good results and insights for hydrologic water balances. For example, simulations by the SPAW model for corn and wheat in significantly different climates demonstrate this capability. This simulation capability will continue to enhance our understanding of the soil water hydrologic system plus provide representations for broad-scale hydrologic simulation models which incorporate the soil water system. Further research with emphasis on plant and soil processes is necessary to develop a level of accuracy and flexibility for good results over a broad range of hydrologic situations and objectives.

The importance of soil water is readily apparent when reviewing a description of almost any hydrologic or agricultural system. The infiltration and evapotranspiration processes, in particular, are strongly related to the time-depth status of the soil-water profile. Most ground-water recharge occurs only after the soil profile becomes significantly wetted. Crop production is highly dependent on having adequate available soil water throughout the growing season. Any attempt to estimate crop yields must include soil-water effects.

The objective of this paper is to briefly review recent advances in the simulation of soil water with particular emphasis on those aspects pertinent to soil-water balance computations for hydrologic and agricultural applications. Mathematical representations of the major processes will be described and simulation models reviewed which integrate these into predictive systems.

RECENT ADVANCES

Numerous developments have occurred in recent years that have significantly enhanced the knowledge and predictability of soil water occurrence. Most of these have been incorporated into computer simulation methods, which in themselves have provided insight and predictive capability. While too numerous to fully describe, several advancements merit review and referencing.

Soil water occurs as a result of several processes that operate within the time line either sporatically or more continuously. Very simply, precipitation is the principle resupply, soil porosity is the storage medium, and evapotranspiration accounts for the majority of depletion. The variables and process equations involved within this total system are numerous and complex. The ability to assemble these equations into computer simulation methods has been the single greatest advance in recent years.

The inputs and descriptions for these soil-water simulations can be categorized into those related to climate, soils, and plants. Climate includes both precipitation and those variables related to the ET potential.

Daily precipitation is the most common input to soil-water balance models. Measured values are most often used if available near the study site. But recent efforts for long-term studies or locations away from measurement locations have caused the development of improved stochastic methods. Richardson (1981) and Woolhiser and Roldan (1982) report good success with a spatially distributed parameter model which maintains the statistical characteristics of the regional precipitation pattern while providing random-based sequences. Orsborn et al. (1982) provide a useful summary to several methods and considerations for precipitation inputs to water-budget simulations.

Most evapotranspiration methods begin with a climatically determined potential ET rate for each day (Saxton et al. 1974a). The inputs vary from only air temperature or pan evaporation to a full compliment of radiation and aerodynamic descriptions. It is often necessary to estimate these inputs; and, again, recent progress has been made. The methods of Richardson (1981), in particular, provided good statistical methods based on limited data. Intercorrelations among precipitation, solar radiation, and air temperatures were considered in their techniques.

Vegetation plays a significant role in the ET process; thus, to simulate soil water requires an adequate description of the growth state and water-related functions. This is especially important where agricultural crops are involved because they rapidly change over the course of a growing season. Descriptions of this biological phase of water-balance computations are some of the most difficult. The above-ground growth is often described by time distributions of crop canopy or leaf-area index (Saxton and McGuiness 1982) and include crop residues. The phenologic development may be a part of crop coefficients (Jensen 1973, Wright 1982) or described separately (Saxton et al. 1974b).

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Root effects are perhaps the least understood. They have been described by some as a time-varying rooting depth with a density distribution (Ritchie 1972), or an effective water uptake time-depth distribution (Saxton et al. 1974b). Taylor and Klepper (1973) provide considerable description for corn, but much actual detail as to how to mathematically represent the root effectiveness is still lacking.

Plant water stress is another area difficult to mathematically represent. Leaf-water potentials and resistances through the leaves, stems, and roots have been described and measured (Salisbury and Ross 1978; Gates 1980, p. 326). Some have incorporated this approach even though definitive numbers are still empirical. The work of Denmead and Shaw (1962) provides a summary of empirical relationships which incorporate the plant response in relation to atmospheric demand and available soil water.

Methods to describe the soil characteristics for holding and transmitting water have recently received considerable advancement. While the concepts of soil tensions and conductivities in relation to soil features have been described for decades, recent mathematical and statistical analyses of voluminous data have provided significant predictive advancements for hydrologic purposes. Rawls et al. (1982) analyzed over 5000 tension curves to develop predictive equations based on soil texture, bulk density, and organic matter. Brakensiek et al. (1981) extended these analyses to determine within-texture variation. Arya and Paris (1981) provided a tension equation based on pore-size distribution which shows good possibility, and Campbell (1974) described predictive equations for tension and conductivity. These and other results will all contribute considerably toward much improved soil relationships for hydrologic soil-water balance computations.

SOIL-WATER BALANCE MODELS

Several models have been developed in recent years that incorporate some or most of the modern process representations just discussed. These have a very wide range of detail and complexity depending upon the data available, the system being represented, crops to be considered, and relative emphasis among the several system processes. A few of these methods will be reviewed to provide a perspective from the simple to more complex. Experience has generally shown that the accuracy of the results is somewhat in proportion to the complexity; thus, each user must select an appropriate method according to the study needs.

A single equation approach was applied by Holtan et al. (1975) and England (1975). Their equation is

$$ET = (GI)\ k\ E_p[(S-SA)/S]^x \qquad [1]$$

where
- ET = actual ET (mm/day)
- GI = growth index of crop (percent)
- k = ratio of ET to pan evaporation for full canopy
- E_p = pan evaporation (mm/day)
- S = total soil porosity (percent)
- SA = available soil porosity (percent), and
- x = exponent estimated to be 0.10.

The GI values reflect crop growth and harvest and are time dependent. The soil storage values S and SA for the root zone approximate water stress although a more precise representation that includes root development and crop stress would significantly improve this aspect.

Soil moisture depletions (actual ET) for irrigation scheduling have been estimated by Jensen et al. (1971) by the relationship

$$ET = K_c\ E_{tp} \qquad [2]$$

where
- ET = actual ET (mm/day)
- E_{tp} = potential ET (mm/day), and
- K_c = a coefficient representing the combined effects of the resistance of water movement from the soil to the various evaporating surfaces, the resistance to the diffusion of water vapor from the surfaces to the atmosphere, and the relative amount of radiant energy available as compared with the reference crop. This inclusive coefficient was estimated as

$$K_c = K_{co}\ K_a + K_s \qquad [3]$$

where
- K_{co} = mean crop coefficient based on experimental data (soil moisture not limiting)
- K_a = ln (AW + 1)/ln 101
- AW = remaining available soil moisture (in)
- K_s = the increase when the soil surface is wetted and equals (0.9 K_c) times 0.8, 0.5, and 0.3 for day 1, 2, and 3 after wetting. This method has worked successfully for irrigated conditions where soil water seldom limits transpiration and considerable calibration of the several coefficients has been conducted.

Other methods have restricted their data inputs to readily available climatologic data which often makes them more practical than more sophisticated methods. Eagleman (1967) described a method based on air temperature and humidity. Brun et al. (1972), Kanemasu et al. (1976), and Rosenthal et al. (1977) described methods using air temperature, R_n, and LAI. Jensen et al. (1971) discussed a similar practical approach for irrigation scheduling, but the technique can be modified and applied to hydrologic needs.

Several methods have been developed which describe the ET processes within the soil-plant-atmosphere system. The soil-plant-atmosphere model (SPAM) described by Lemon et al. (1973) and Shawcroft et al. (1974) treats the ET and plant growth characteristics in detail. A similar model reported by

Hanks et al. (1969) and Nimah and Hanks (1973a, 1973b) concentrates more on the soil moisture and its plant interaction.

Even more sophisticated models are being developed as new capability in computing capacity and ease of programming is available. Kristensen and Jensen (1975) applied a detailed ET model to the crops of barley, sugarbeets, and grass over a 4-year period with reported accuracy of 10 percent. Van Bavel and Ahmed (1976) described a model of the soil moisture flow and root uptake programmed in CSMP. Hansen (1975) reported a more general model of the soil-plant-atmosphere system programmed in DYNAMO II. Lambert and Penning deVries (1973) presented a model of the ET system called TROIKA. Van Keulen (1975) presented a model programmed in CSMP with all details well described, and Makkink and van Heemst (1974) showed the application results of a similar model.

A comprehensive model to compute daily actual ET from small watersheds was developed and reported by Saxton et al. (1974b) and revised as shown by Sudar et al. (1981). This model, shown schematically in figure 1, separates the major climatic, crop, and soil effects into a calculation procedure with emphasis on graphical representation of principle relationships. Calculated amount of interception evaporation, soil evaporation, and plant transpiration are combined to provide daily actual ET estimates.

Beginning at the top of figure 1, intercepted water at the plant and soil surfaces is considered to have first use of the potential ET energy, and no resistances are imposed. Remaining potential ET is divided between soil water evaporation or plant transpiration according to the plant canopy present as described by soil shading on leaf-area index. Actual soil evaporation is the potential evaporation limited by soil water content at the surface, except in the very wet range; thus, it represents the traditional two-stage drying sequence. For dry soil with a plant canopy, a percent of the unused soil evaporation potential is returned to the plant transpiration potential to account for reradiated energy from the heated soil and air. Actual transpiration is computed through sequential consideration of plant phenology to describe the transpirability of the existing canopy, a root distribution to reflect where in the soil profile the plant is attempting to obtain water, and a water stress relationship which is applied to each soil layer and is a function of the plant-available water of the soil layer and the atmospheric demand on the plant. The soil water is adjusted by abstracting the daily actual ET from each rooting layer, adding daily infiltration computed from daily precipitation minus measured or estimated runoff, and estimating soil water redistribution and percolation by a Darcy-type unsaturated flow computation.

EXAMPLES OF SOIL WATER SIMULATIONS

Results using the SPAW model just described readily illustrate the computations which can now be obtained for water balance simulations of the soil water. This model utilizes minimal input data and moderately complex computations to provide quite reasonable computation costs of 1 to 2 cents per computation day on IBM-Amdahl large-scale computers. The accuracy is accordingly not as precise as that expected from more complex models, but accurate enough for most hydrologic water balances.

Figure 2 shows the time distribution of soil water for several layers of a silt loam soil during the growing season of a corn crop. The simulated results provide a reasonably accurate representation of the observed data which were obtained with the neutron scatter technique at three sites within a 32-ha field. The dynamics of the soil water in the upper layers are quite apparent and resulted from the 780 mm of precipitation during the April-October growing season.

The simulations in figure 3 demonstrate a significant contrast to those in figure 2, where the data are for a growing season of winter wheat where nearly all precipitation occurs during the winter months. With appropriate climatic data and crop and soil parameters, the SPAW model was used to provide good water-budget simulations. The silt loam soils are fallowed for 1 year prior to the winter wheat crop year because annual precipitation averages only 300 mm in this location.

The data in table 1 further illustrate the effectiveness of simulating soil water hydrology. These values were computed using measured climatic data, soil characteristics from soil series descriptions, and mean growth characteristics for corn (maize) for eleven selected sites along a transect which had annual average precipitation ranging from 450 mm to 1050 mm and lake evaporation (potential ET) ranging from 1040 mm to 1890 mm during the 10 years of continuous simulation for each site. The columns of table 1 represent the U.S. Weather Bureau station numbers in Kansas and Missouri and average annual values of potential ET, actual ET, soil water evaporation, transpiration, intercepted water evaporation, precipitation, runoff, deep percolation, plant stress (annual accumulative index), and crop grain yield reduction (annual accumulative index). Only precipitation and potential ET (reduced pan evaporation) are measured values. The soil water budget is complete as shown except for a change in the soil water storage.

The average values of table 1 show the general rainfall disposition into and out of the soil profile. More detailed outputs (which are readily available) show the dynamic changes that occur day to day (like those of figures 1 and 2) and result in many important interactions in relation to hydrology and crop production. The consistent trends and relative magnitudes of the table 1 values show the adaptability and utility of simulation models such as SPAW even without voluminous

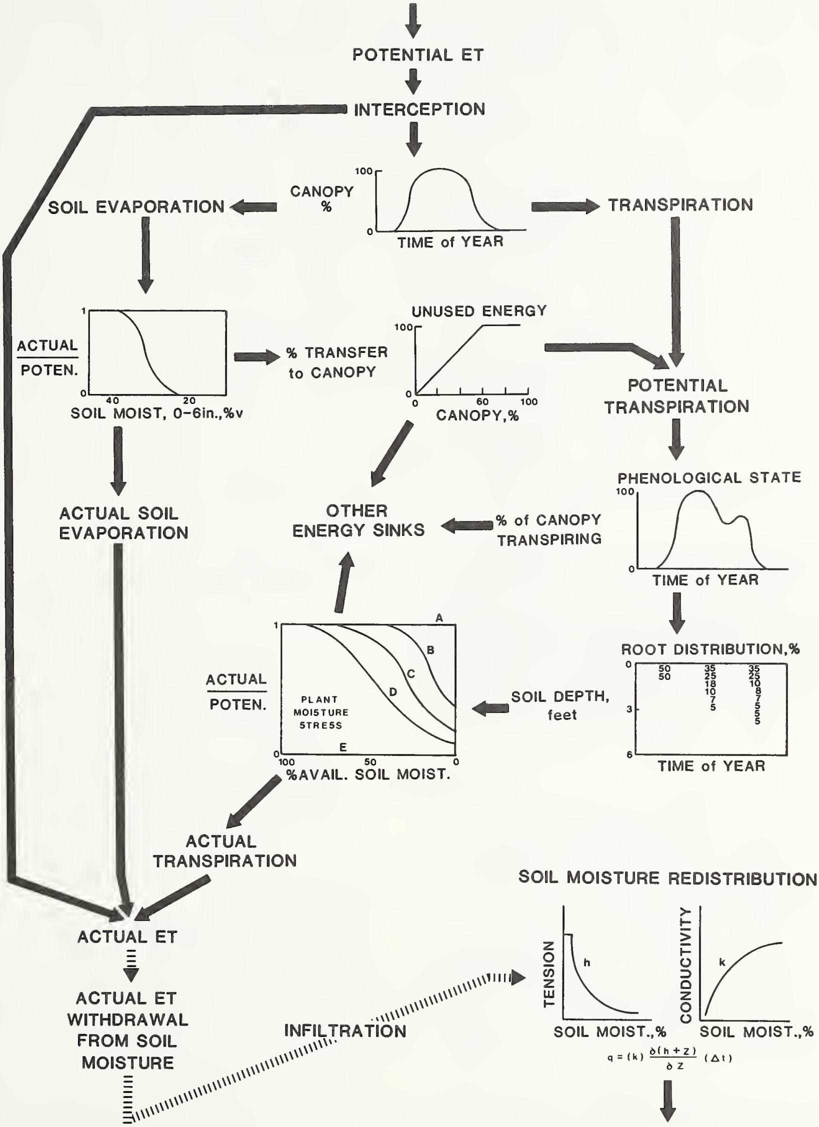

Figure 1. Schematic computational sequence of the SPAW model (Saxton et al. 1974b; Sudar et al. 1981).

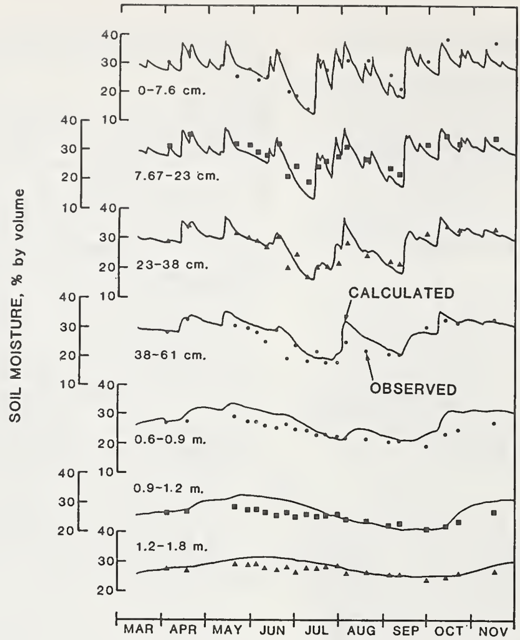

Figure 2. Observed soil water by soil layers versus that simulated by the SPAW model for Iowa corn field during 1970 (Saxton et al. 1974b).

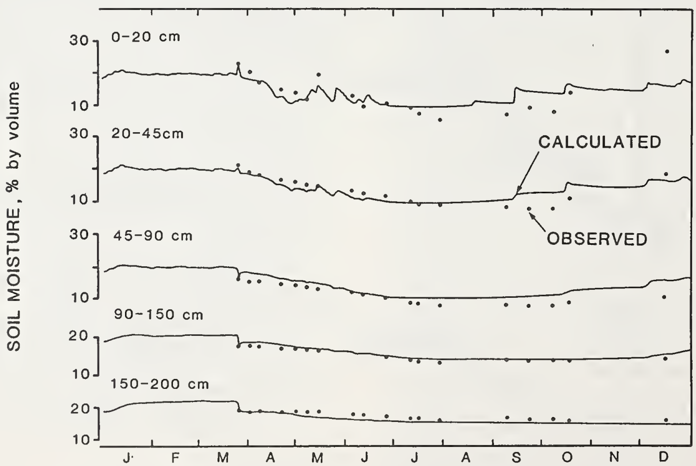

Figure 3. Observed soil water by soil layers versus that simulated by the SPAW model for eastern Washington wheat during 1980.

Table 1.--Mean annual water budget for ten years (1967-1976) as simulated by the SPAW model

Station ID	Pot. ET	Act. ET	Soil evap.	Plant trans.	Inter. evap.	Prec.	Run-off	Deep perc.	Plant stress	Yield
	mm								-Dimensionless-	
1699 KS	1887	391	132	137	122	457	61	3	41.6	8.4
5852 KS	1689	497	218	142	137	589	81	3	33.7	7.5
4857 KS	1438	586	226	208	152	704	113	0	28.7	6.6
8259 KS	1313	571	84	335	152	861	185	94	16.2	3.4
6333 KS	1321	584	91	330	163	892	180	114	16.4	3.7
6014 KS	1280	584	91	338	155	919	206	122	14.0	3.0
3300 MO	1224	683	152	353	178	871	135	64	9.8	2.0
6563 MO	1102	665	157	325	183	871	122	89	5.8	1.3
4978 MO	1062	653	168	305	180	937	218	71	5.9	1.5
5671 MO	1044	645	145	312	188	1054	292	104	6.3	1.1
6633 MO	1016	652	160	302	191	1006	274	86	5.0	1.2

verification data. However, as in this case, some data are nearly always necessary for original model calibrations.

RESEARCH NEEDED

While there have been significant advances in nearly all aspects of soil-water simulations, there are many facets that need to be further defined. Always, the accuracy of the simulation method must be considered with respect to the study objectives. For broad-scale, longer-term water budgets, several existing models may be adequate. For more defined conditons where crop, soil, or climatic conditions may result in subtle, yet very meaningful differences, the degree of accuracy is severely limiting.

Essentially every relationship in every simulation method could command further refinement. Obviously, some are more important--depending on study objectives. Thus, sensitivity analyses should be applied to suggest relative importance and accuracy. In general, it appears at this time that the plant physiology descriptions are the least well known. Root distribution and soil-root interactions, within plant reactions, and the leaf-atmosphere boundary layer, all play a dominent role in coupling the soil water to the evaporative demand. Good simulation descriptions for this system are yet to be developed.

The physics of soil water storage and conductivity have been diligently studied for many years, yet the description of characteristic soil-water relationships over a landscape is possible only in a general way because of spatial variation and complex changes with the biological and physical soil development processes. Methods to adequately represent the soil-water relationships for applied simulation need considerable further study. Each simulation method, data base, and internal representation needs careful evaluation to define the research for additonal applied knowledge.

CONCLUSIONS

Soil water hydrology is an important portion of the overall hydrologic regime of any landscape and merits detailed study and evaluation just as has surface water hydrology and ground water hydrology. While soil water hydrology is quite dependent on climatic inputs, soil characteristics, and the vegetation being grown, there have been significant recent advacements which describe these physical processes as they interact with soil water and each other. These include several simulation models that provide good results and insights for hydrologic water balances. Simulations by the SPAW model for corn and wheat in significantly different climates demonstrate this capability.

Simulation models of soil water have a broad range of detail and complexities. The amount of input required and accuracy of results are closely related to this spectrum. This simulation capability will continue to enhance our understanding

of the soil water hydrologic system. It will also provide representations for broad-scale hydrologic simulation models which incorporate the soil-water system. Further research with emphasis on plant and soil processes is necessary to develop a level of accuracy and flexibility for good results over a broad range of hydrologic situations and objectives.

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NITROGEN-TILLAGE-RESIDUE MANAGEMENT (NTRM) MODEL SYSTEM: AN OVERVIEW

M. J. Shaffer, S. C. Gupta, and D. R. Linden[1]

INTRODUCTION

In recent years, a need has been identified to develop integrated guidelines for the management of tillage practices, crop residues, and nitrogen fertilizers in U.S. agriculture. In 1979, the USDA-ARS initiated a national research program to develop these guidelines. A number of ARS research locations and cooperating universities have been involved in this work. The development of a comprehensive computer simulation model system for nitrogen-tillage-residue management applications at various levels was a prime objective of the overall effort.

To date, models have been developed at two levels of detail. A farm level model called COFARM (coordinated farm and research management) has been developed by ARS, St. Paul, with the cooperation of the University of Minnesota. This model provides interactive farm and field data management as well as site-specific farm management recommendations in the areas of tillage, nitrogen fertilizers, crop residues, crop yields, nitrate leaching, and soil erosion. A research and extension data base is being developed as individual farm users supply information to the system.

A second model has been developed at the research level to provide a detailed analysis of the soil-plant-water continuum. This model, known as the nitrogen-tillage-residue management (NTRM) research model, was developed by the ARS, Soil and Water Management Research Unit in St. Paul, Minnesota, with assistance from the University of Minnesota, the ARS research unit at Morris, Minnesota, and other cooperating ARS locations and universities.

The objective of this paper is to present an overview discussion of the development, structure, and application of these modeling tools.

COFARM MODEL

The principal components of COFARM are illustrated in figure 1. The COFARM data management submodel (fig. 2), supplies specific farm management histories and soils data for each field. The soils information is obtained, in part, from data bases such as SCS Soils-5. Climate data are included to provide a range of crop yields and management responses as a function of local climate variability.

Simplified equations were developed for corn growth, water and nitrogen stress, soil nitrogen transformations, water flow, solute transport, transpiration, evaporation, and tillage and residue effects. Both water and nitrogen budgets for the soil-crop system are determined throughout the growing season. Information used to develop and support these relationships was obtained from field plot data, applications of the NTRM research model, and other information from the literature. Depending on the user's request, sets of model projections are made to illustrate the response of the crop and each soil type under a range of climate and management conditions. Results can be returned to a remote terminal located on the farm, or the entire COFARM model can be run on a suitable stand-alone microcomputer. Figure 3 shows a comparison of

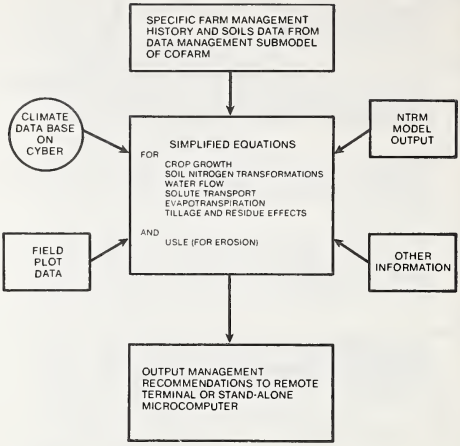

Figure 1. COFARM model for site-specific management.

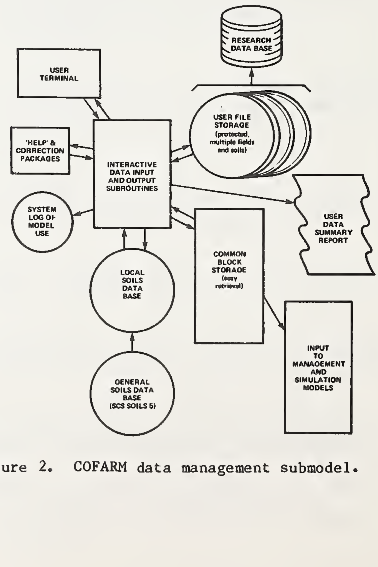

Figure 2. COFARM data management submodel.

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calculated and observed corn yield data for a 14-year period at Lancaster, WI. An R^2 value of 0.78 was obtained using the simplified approach in the model.

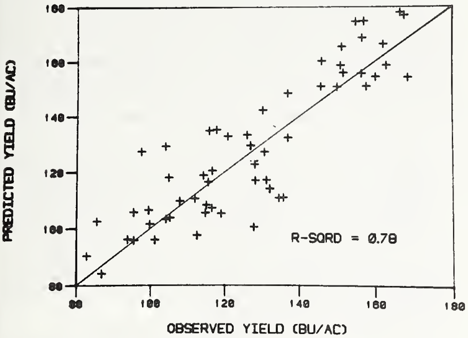

Figure 3. COFARM corn yields.

NTRM MODEL

The unsaturated (vadose) zone portion of the NTRM model (fig. 4), was developed over a period of about 3 years by utilizing and adapting some existing submodels and by developing certain others. A team approach was utilized in which soil physicists, soil chemists, hydrologists, engineers, plant physiologists, soil microbiologists, and computer scientists contributed to the development of the overall model.

The primary objective was to develop a comprehensive, physically significant model of the soil environment and its effects on crop growth. Emphasis was placed on the tillage, nitrogen, and residue aspects of the system. The scope of the model was kept wide enough to allow model applications in the areas of research, crop and soil management, and teaching.

A cross section of the crop-soil-water continuum and aquifer being simulated with the NTRM model is shown in Figure 5. Note the basic physical, chemical, and biological processes which are being modeled. The aquifer portions of the model are a separate set of previously developed submodels which require input from the unsaturated zone simulators. Likewise, the soil temperature submodel is a stand-alone program which generates inputs for the overall model.

The Detailed Return Flow Salinity and Nutrient Simulation Model reported by Shaffer et al. (1977) was used as a core around which to build the NTRM model. This irrigation return flow model already contained relatively comprehensive submodels for water flow, nutrient transformations, salt reactions, and salt transport. One current version of this model (Shaffer and Gupta 1981) has been used to simulate solute reactions and transport in land treatment of municipal wastewater effluents.

The original core model has a history dating back to the early and middle 1960's when G. R. Dutt of the University of Arizona and K. Tanji of the University of California, Davis, began developing the first submodels, primarily in the

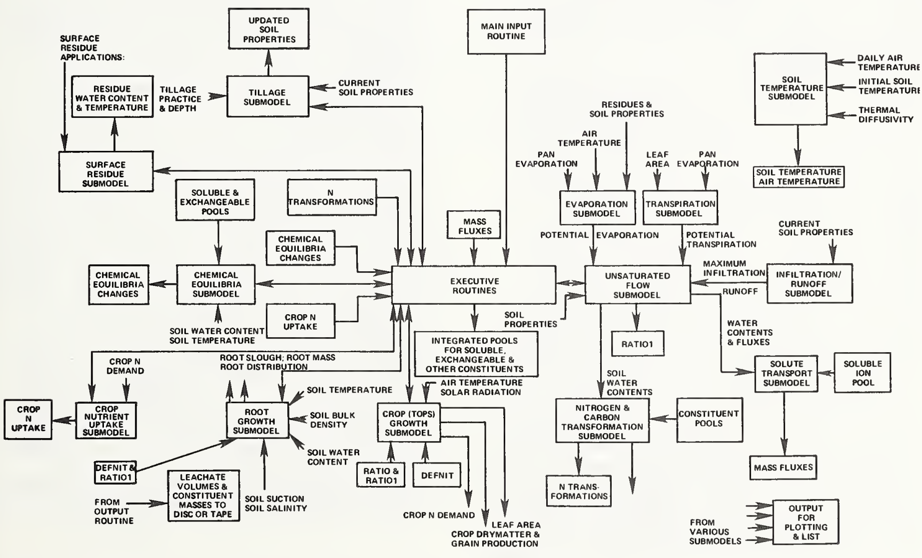

Figure 4. NTRM model - general flow chart of vadose zone simulation.

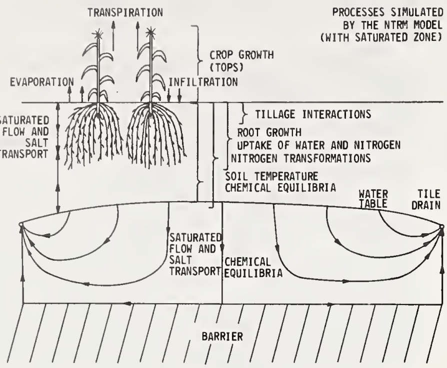

Figure 5. Processes simulated by the NTRM model (with saturated zone).

area of soil chemistry associated with irrigation in the Western United States (Dutt 1961, Dutt and Tanji 1962). By the early 1970's, the modeling work had been extended to include unsaturated flow and nitrogen transformations under a growing crop (Dutt et al. 1972, Shaffer et al. 1969, Shaffer and Dutt 1973). The model was also extended by personnel at the U.S. Bureau of Reclamation to include water flow and chemical processes in the aquifer below irrigated areas (Ribbens 1970, Shaffer and Ribbens 1974, Shaffer et al. 1977). In the late 1970's the model was adapted by the USDA-ARS group in St. Paul to simulate nutrient transformations, solute chemistry, and water flow processes during land treatment of sewage effluents (Gupta et al. 1978).

In late 1979, work began on the initial development of the NTRM model (Shaffer 1980). The Nebraska corn growth model (CORNGRO) (Childs et al. 1977) was incorporated with modifications as a submodel for crop growth. Submodels or capabilities for additional crops will be added as the NTRM model system is further developed. A dynamic root growth model (Shaffer and Clapp 1982) was developed from theory to complement the corn growth model for top growth and total dry matter production. The unsaturated flow model (Dutt et al. 1972, Shaffer and Gupta 1981), originally based on work reported by Hanks and Bower (1962), was updated to include the layered case; upper boundary conditions were included which were more suitable for rapid water fluxes and surface evaporation. The evaporation and infiltration submodels developed by Linden (1979) were incorporated into the overall model.

A second nitrogen transformation submodel developed by Molina et al. (1982), which is more detailed and less empirical than the Shaffer N transformation model in the areas of crop residue and soil organic matter transformations, was incorporated into the model. This submodel also includes the options of using Shaffer's transition state submodel for nitrification (Shaffer et al. 1977) and an expression for urea hydrolysis previously reported by Shaffer et al. (1969). N^{15} tracer capabilities also were incorporated into the new N transformation model and the overall NTRM model.

In the areas of crop residue and tillage, new submodels and information transfers were developed to simulate the appropriate interactions. Capability was added to allow decay of residues on the soil surface and interaction of these residues with crop growth, heat flow, and water flow. Similar capabilities also were included for residues incorporated into the soil.

The effects of tillage practices on soil physical, chemical, and biological properties are simulated in the model. The effects of those changes on crop growth are then modeled using a separate set of relationships.

The soil temperature model reported by Gupta et al. (1981) was incorporated into the NTRM model system. This submodel is operated as an independent program with input to the interactive model via data file transfers.

Capability was retained in the model to generate soil leachate volumes and constituent concentrations suitable for input to the aquifer submodels (Ribbens and Shaffer 1976, Shaffer et al. 1977).

The basic structure of the vadose zone portion of the NTRM model is shown in figure 4. The major computational submodels include soil temperature, unsaturated flow, infiltration, transpiration, evaporation, tillage, surface residues, nitrogen transformations, chemical equilibria, salt transport, crop nutrient uptake, crop growth, and root growth. In addition, there are two executive subprograms (EXECUTE and COMBINE) which control the logic, flow, and integration of the computations; a main input subprogram; and a number of smaller subroutines (not shown) with specific functions, including data output, data transformations, file positioning, rate calculations, mass balance checking and maintenance, and other duties.

The NTRM model is written in FORTRAN IV computer language for Control Data Corporation (CDC) CYBER and Cray Research, Inc. CRAY-1A machines. A version of the model source code meeting 1977 ANSI FORTRAN standards is available to outside users upon request. In addition, an extensive operating system (Shaffer and Pierce, 1982) for the NTRM model has been developed which makes it relatively easy to access and use the CDC and other versions of the model. An outside user can enter the CDC CYBER system from a remote time share terminal and operate the model.

Storage requirements for the NTRM model on the University of Minnesota CYBER 74 are about 150K binary words of central memory. The model uses 18 disc or tape files during execution. Execution times for a growing season vary with the number and type of submodels being utilized. With the entire model turned on, run times for a growing season should not exceed 4 to 5 seconds (CRAY-1A computer) at a cost of about $2.50. Long-term and other runs using special reduced configurations of the model can be made at a cost of about $0.50 or less per season.

NTRM MODEL VALIDATION

Field testing of the overall integrated NTRM model has been a continuing process as additional data sets are analyzed. Corn yield results for four different locations, three in Minnesota and one in Ohio are presented in figure 6. Yield differences seen here are primarily the result of climatic differences, as opposed to those induced by management.

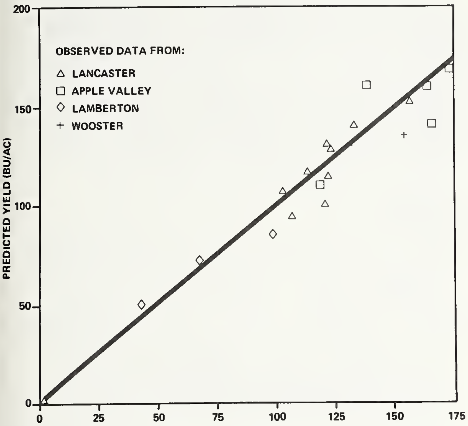

Figure 6. NTRM model - corn yields.

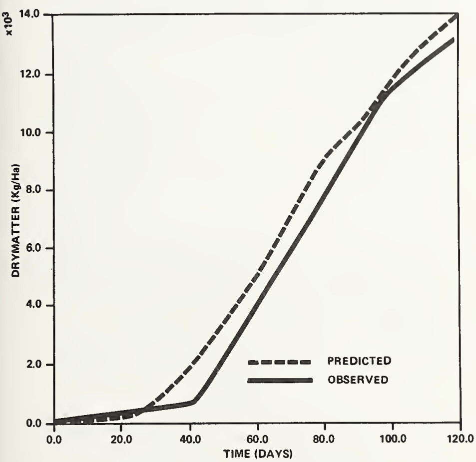

Figure 7. Crop dry matter production for predicted and observed corn data collected on a control at Apple Valley, MN.

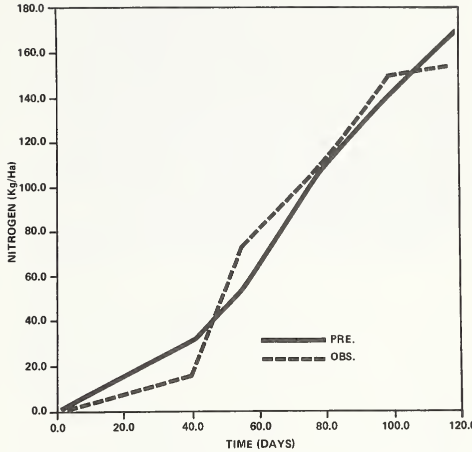

Figure 8. Crop nitrogen uptake for predicted and observed corn data collected on a control site at Apple Valley, MN.

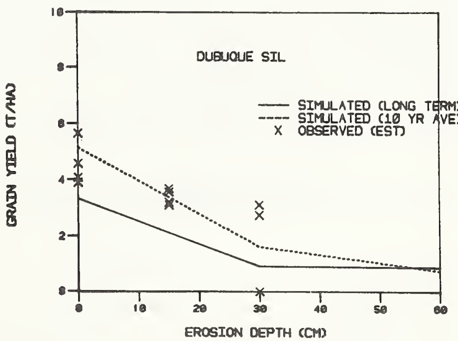

Figure 9. Corn yields at various erosion levels.

Figures 7 and 8 contain crop dry-matter production and crop nitrogen-uptake curves, respectively, for predicted and observed corn data collected on a control site at Apple Valley, Minnesota. The model run indicated that nitrogen was not limiting and that a relatively shallow root system would be expected due to ample nutrient availability and moist soil conditions at shallow depths. This was confirmed by root samples in the field.

Figure 9 illustrates the results of a soil erosion-productivity study on continuous corn using the NTRM model. Three soils were analyzed at 0, 15, 30, and 60 cm of erosion for long-term

(100 year) and short-term (10 year) periods. Fertilizer nitrogen was applied at an annual rate of 250 kg/ha. The soils analyzed included Fayette silt loam, a deep loess soil; Dubuque silt loam, which is shallow to bedrock, and the Dakota fine sandy loam, which is shallow to coarse materials. Literature values for corn grain yields at 0, 15, and 30 cm erosion and the Dubuque soil are plotted for comparison with model results. These data were obtained from soil survey publications and data bases, and research plot results. The published yields were normalized to reflect current management practices and varieties.

Figures 10 and 11 illustrate the application of the NTRM model in a long-term study involving wheat grown under dryland conditions in the Great Plains area of the United States (Larson et al. 1983). In this situation, wheat production was simulated for continuous and wheat-fallow management practices. Probability curves were developed for each management practice over a 100-year period.

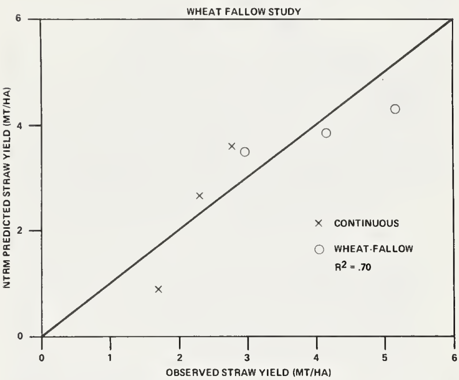

Figure 10. Observed vs. predicted wheat straw yields.

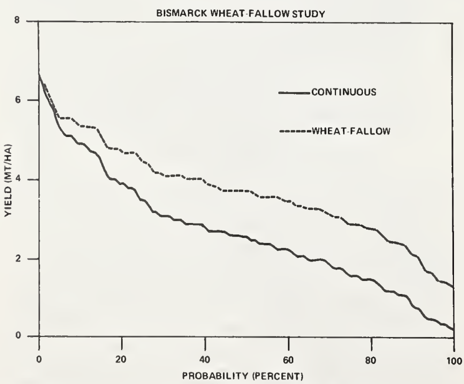

Figure 11. Probability of wheat straw yields under continuous and wheat straw conditions (Bismarck, ND).

SUMMARY

The NTRM system of models currently includes a farm level model (COFARM) and a research model (NTRM). Development of these tools has allowed the interchange of ideas, methods, and concepts between different levels of modeling detail. The history, structure and validation of these models were presented in general terms to give the reader an introduction to the simulators. The sample applications served to demonstrate use of the models in solving real world problems.

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MODELS NEEDED FOR FARM PLANNING

Gerald M. Darby[1]

Soil Conservation Service (SCS) personnel help the farmer plan and apply soil and water conservation management systems. In addition to this help, the farmer needs to know how the new management systems will affect such things as cost-returns, pest control, a need for new cultivars, and government commodity control programs. Neither a soil conservationist nor a county extension agent can be expected to provide all these answers without special tools in the form of data sets, models, and state-of-the-art computers.

SCS uses two models extensively in this planning process. They are the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation (WEQ). USLE is used to predict the average rate of soil loss by sheet and rill erosion, and the WEQ is used to predict soil loss from wind erosion. The factors for the equations are displayed in tables, charts, and graphs; as tables on a slide rule; or entered in a programmable calculator. Assistance to our field people in using these data is provided by the SCS State Agronomist with guidance from other SCS specialists and Agricultural Research Service (ARS) scientists.

There are still weaknesses in these two equations. In the Northwest, additional USLE data are needed for very steep slopes and for the effects of freezing and thawing on erosion rates. For the WEQ, additional data on climate are needed. Also needed are small-grain equivalencies for range plants and additional crops that are grown where wind erosion is a problem. Gathering these data is a formidable job undertaken by ARS.

A very important need of the farmer is a system for estimating both the annual out-of-pocket cost and long-term amortized cost of erosion in terms of nutrient losses, reduction in crop yield and property value, and on-farm property damage. In some cases erosion costs the farmer less during the short term than does the establishment of conservation practices. A computerized model could help the farmer look beyond the short-term costs. It could also help him and the conservationist develop the most economical system for erosion control.

Farmers need to know the amount of crop residue required for soil protection. USLE can help one determine this through the crop management factor. This equation, however, will not help the farmer evaluate crop residue for use as a source of nutrients, as a soil conditioner, for hay, or for grazing. In determining the residue's value for grazing, damage to soil structure from hoof traffic would need to be estimated as well as loss of residue for erosion control.

Special crop and soil management problems in the semiarid and subhumid zones necessitate special information systems. In some of these areas annual cropping is not economical. It does not always pay to apply fertilizer because in many years moisture is growth limiting. In some areas certain crops would produce better in certain years than other crops. With a model based on soil moisture conditions and rainfall probabilities at planting time, SCS could help the farmer determine if he should plant or fallow the field for that year, if fertilizer would be profitable, what fertilizer should be used, and perhaps what crop to plant. The farmer could not be assured that his decisions would guarantee a profit, but he could base them on the probabilities produced by such a model. Considerable work has been done to help farmers make important crop management decisions. In Montana, farmers are being encouraged to use a flexible cropping system based on yield data from prior years correlated with weather conditions at planting time. Commonly the farmers there have used wheat-fallow systems. However, in much of this area there is normally enough rainfall for annual crop production. Adequate rainfall eliminates the need for a fallow year.

In Montana and other Great Plains areas where land is fallowed, excess moisture drains through the profile, flows along an impervious layer that is saline, and surfaces at a lower elevation as a saline seep. Information, models, and computers are available for use in helping farmers understand how to prevent these saline seeps and make wise management decisions. Some applicable models are Flexcrop; Soil, Plant, Air, and Water (SPAW); Nitrogen, Tillage, Residue Management (NTRM); Soil-Crop Management System (SCMS); and Cooperative Farm Research Management (COFARM).

Another modeling effort which should be addressed deals with the effects of pesticides on surface and ground water contamination. USDA is actively promoting conservation tillage as an economical means of reducing soil erosion. Present research, however, is not conclusive in determining the effect of conservation tillage on surface and ground water contamination by pesticides. Models are needed for evaluating fates of pesticides applied in both conservation tillage and conventional tillage systems. These would be useful in comparing erosion control alternatives and their effects on water quality.

Today's farmers are business managers in the truest sense. Many of them have multimillion-dollar operations. They are responsible for efficient operations of complicated machinery. They buy and use expensive chemicals, some that can be toxic to themselves and others if not used properly. Because of these things, research scientists, extension specialists, and soil conservationists must do all that they can to provide sound data to the farmer. Their cooperation in developing and using effective models will help them to do this.

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A GENERAL OVERVIEW OF CROP SIMULATION

Donald N. Baker[1]

INTRODUCTION

We begin this overview by defining the term "simulation" as the mathematical representation of a system. If it represents a system which changes in time, we call it dynamic simulation. This is classified as modeling, but modeling has a much broader connotation.

Other simpler models have been designed to help the farmer to select varieties, row spacings, etcetera; and from a simple equation summarizing field data, they may help him to calculate the yield penalty to be expected from late planting. Examples here are the models of Halvorsen and Kresge (1982) (wheat) and Palmer (1983) (soybean). Another example of a simple model is the DD50 model of Huey et al. (1981) in Arkansas which predicts the phenological development of rice from heat units above a 55 degree F base.

Numerous phenological models (especially of the small grains) have been built for the purpose of yield forecasting. In the best of these models, field data from a wide range of conditions are summarized to obtain reduction factors to be applied to the various components of yield at the different plant developmental stages. For example, a low value of plant available water during tillering might cause a certain reduction in tiller numbers. A certain degree of cloudiness during head differentiation might cause some reduction in kernel numbers, while cool conditions might lengthen the grain filling period and increase kernel weights. Yield is computed by multiplying three yield components, head numbers, kernels per head and weight per kernel.

The multiple regression models, like those of Feyerherm and Paulsen (1981) or Thompson (1969), are a simpler subset of the phenological models. The phenological models decrement from an optimum crop performance data base which is specific to a particular site and cultivar. Soil conditions, including fertilizer, tillage and drainage are among the site specific input variables. The regression models decrement on the basis of calendar date rather than crop developmental stage. Because changes in environmental factors, such as temperature, frequently affect different processes in different ways, and because of the interrelatedness of these processes, statistical and phenological models can only be used for interpolation. They cannot be used for extrapolation (c.f. Neter and Wasserman 1974).

The remainder of this paper deals with crop simulation models. There are 20 to 25 teams in the United States and overseas building crop simulation models. Among the crops which have been modelled are citrus, peanuts, sugar beets, corn, sorghum, wheat, rice, barley, white potato, cotton, soybean and alfalfa. Several models, developed by different groups, exist for some of these species. Most of them are materials balances. They vary widely in terms of the array of processes treated and the ways they are treated. They also vary greatly in their developmental status and in the level of consultative support available to the potential user. A list of some published modeling efforts is contained in table 1.

STRATEGY

The structure, strategy, and content of crop simulation models is dictated mainly by the disciplinary background of the modeler and the modeling group. The impact of the disciplinary background of the modeler on model structure is often seen in the modeler's perception of the consequences of including or deleting certain mechanisms and in the data base that is likely to be available or that the modeler will assume can be obtained on which to build his model. It is often claimed that model structure is, or should be, dictated by the intended purpose or application (of the model), but the purpose of all crop models is to predict crop response to exogenous variables, and the "purpose" claim often has the appearance of a crutch to help the modeler deal with the feeling that he is not, or need not be, involved in a sufficiently broad-based multidisciplinary effort. The question of the need for a multidisciplinary approach was resolved years ago in the structure of agricultural university faculties and teaching curricula. I might note that most crop models, today, are not being developed by crop physiologists, although applications of physiologically based models in crop breeding, irrigation, tillage and fertilizer management appear promising (Baker et al. 1979, Jenkins et al. 1973). Most crop models today are being developed by agricultural and industrial engineers, soil physicists and entomologists. Thus, most crop simulation models treat relatively few physiological processes explicitly with rate equations based on measurements of process rates under controlled conditions. Rather, most models are based on "surrogate" variables and literature data or measurements made in field-grown crops.

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Table 1.--Some process level crop simulation efforts.

Authors	Institutions	Model name	Species	Processes treated
Acock, B., V.R. Reddy, F.D. Whisler, D.N. Baker, J.M. Mc Kinion, H.F. Hodges, K.J. Boote	USDA-ARS, Miss. State U. U. of Florida	GLYCIM	Soybean	Photosynthesis, respiration, transpiration, growth and morphogenesis. Incorporates RHIZOS
Allen, J. and J.H. Stamper	U. of Florida	CITRUSIM	Citrus	Photosynthesis
Angus, J.F., and H.G. Zandstra	CSIRO, Australia, International Rice Research Institute	IRRIMOD	Rice	Growth, phasic development, soil water flow, soil nitrogen transformations
Arkin, G.F., J.T. Ritchie, and R. L. Vanderlip	Texas A&M U. USDA/ SEA, and Kansas State U.	SORG	Sorghum bicolar	Photosynthesis, respiration, transpiration and evaporation
Baker, D.N., J.R. Lambert, Whisler, and J.M. McKinion	USDA/SEA at Mississippi, Clemson U.	GOSSYM	Cotton	Photosynthesis, respiration, growth and morphogenesis. Incorporates RHIZOS
Brown, L.G., J.D. Hesketh, J.W. Jones, and F.D. Whisler	Mississippi State U.	COTCROP	Cotton	Photosynthesis, respiration, transpiration, runoff, drainage, nitrogen uptake, denitrification, leaching, organogenesis, partioning and growth
Childs, S.W., J.R. Gilley, and W.E. Splinter	U. of Nebraska	Unnamed	Corn	Photosynthesis, respiration, transpiration, growth, soil evaporation, and soil water flows
Curry, R.B., G.E. Meyer, J.G. Streeter, H.L. Mederski, and A. Eshel	Ohio Agr. Res. & Development Center	SOYMOD OARDC	Soybeans	Photosynthesis, respiration, translocation and evaporation
Duncan, W.G.	U. of Florida, U. of Kentucky	SIMAIZ	Corn	Photosynthesis, processes involved in setting seed number and seed size
Duncan, W.G.	U. of Florida, U. of Kentucky	MIMSOYZ	Soybeans	Photosynthesis, nitrogen fixation, assimilate redistribution, processes for setting
Duncan, W.G.	U. of Florida, U. of Kentucky	PEANUTZ	Peanuts	Photosynthesis, nitrogen fixation, processes for setting seed number and seed size
Fick, G.W.	Cornell University	ALSIM	Alfalfa	Photosynthesis defined as crop growth rate, and partioning
Holt, D.A., G.E. Miles, R.J. Bula, M.M. Schreiber, D.T. Doughtery, R.M. Peart	Purdue University, USDA/SEA	SIMED	Alfalfa	Photosynthesis, respiration, growth, translocation, and soil moisture uptake
Kercher, J.R.	Lawrence Livermore Lab.	G JW1	general	Photosynthesis, transpiration, translocation
van Keulen, H.	Netherlands Agr. U.,	GRORYZA	Rice	Gross assimilation and respiration
van Keulen, H.	Netherlands Agr. U., Wageningen	ARIDCROP	Natural vegetation in semi-arid regions	Photosynthesis, respiration, transpiration, and water uptake
Loomis, R.S. and E. Ng	U. of California, Davis	POTATO	Potato	Photosynthesis, respiration, transpiration, water uptake, growth, development and senescence
Loomis, R.S., J.L. Wilson, D. W. Rains, and D.W. Grimes	U. of California, Davis	COTGRO	Cotton	Photosynthesis, respiration, transpiration, water uptake, growth, development, flowering, fruit development, senescence, and soil heat flux
Loomis, R.S., G.W. Fick, W.A. Williams, W.H. Hunt, and E. Ng	U. of California Davis	SUBGRO	Sugar beet	Phogosynthesis, respiration, transpiration, water uptake, growth, development, and senescence
Marani, A.	The Hebrew U. of Jerusalem	ELCOMOD	Cotton (Acala)	Photosynthesis, respiration, growth, morphogenesis, ET, nitrogen uptake, and gravitational soil wetting
McMennamy, J.A., and J.C. O'Toole	International Rice Research Institute	RICEMOD	Rice	Photosynthesis, respiration, growth
Orwick, P.L., M.M. Schreiber, and D.A. Holt	Purdue U.	SETSIM	Setaria	Carbon flow, photosynthesis, respiration, growth, and translocation
Ryle, G.J.A., N.R. Brock--ington, C.E. Powell, and B. Cross	Grassland Research Institute, Hurley, Berkshire England	Unnamed	Uniculum barley	Photosynthesis, assimilate distribution, and synthetic and maintenance respira tion
de Wit, C.T. et al.	Netherlands Agr. U., Wageningen	PHOTON and BACROS	Any crop	Photosynthesis, respiration, transpiration, reserve utilization, water uptake, and stomatal control

The matter of the so-called surrogate variable is interesting. For example, some modelers calculate dry matter production rate from the estimated transpiration rate, citing Tanner's (1974) observation of "an impressive linearity between transpiration and yield." There are a number of theoretical reasons why we would not expect a constant relationship between photosynthesis and transpiration. For several years prior to the appearance of these models, we (Baker and Musgrave 1964) had been making 15-minute measurements of gas exchange rates in crop canopies. The data in figure 1 are typical. Although curvature is observed under some circumstances, as the data in figure 1 show, the idea works fairly well in cotton (probably because it is a xerophyte). Obviously, there is an impressive curvilinearity in the relationship for corn.

In any software development project, some assumptions must be made about the availability of hardware at the end of the software development period. In other words, how big can a model be before the user (for example a farmer) can not afford to run it? In Figure 2, McKinion and Baker (1982) have graphed industry data on costs of various components of the computer system. Some of these costs are declining dramatically. In table 2 and in figure 2 data from Finkler (1983) provide a market summary. Overall sales of all classes of computers will gain, but the micros, which are now showing up on the farm, will gain dramatically. In addition to crop simulation, some of these are capable of logging climate data in real time and performing process control, for example fertigation.

THE SYSTEM

The dynamic components and possible control points of a typical crop production system are identified in Figure 3. Most models attempt to deal with the weather variables as inputs and with the above-ground processes. Most include only a very simple treatment of soil processes, although a few provide a detailed, even two-dimensional treatment of soil processes. Some are designed to account for insect damage. None, that I know of, account for weed damage.

The notion of the materials balance is conveyed in Figure 4. Flow of carbon is shown as a continuous process through photosynthesis to various cotton plant parts, with economic yield being the time integral of flows into bolls. Similar flows of nitrogen from the soil are also depicted. Photosynthesis is regulated by temperature, leaf water potential and radiation. Growth is regulated by tissue turgor and temperature. It may be limited by the supply of metabolites.

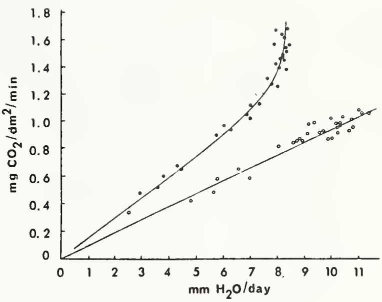


Figure 1.--Crop canopy photosynthesis vs. transpiration in corn (closed circles) and cotton (open circles).

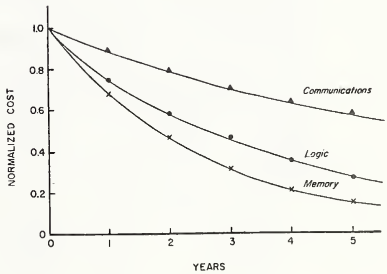
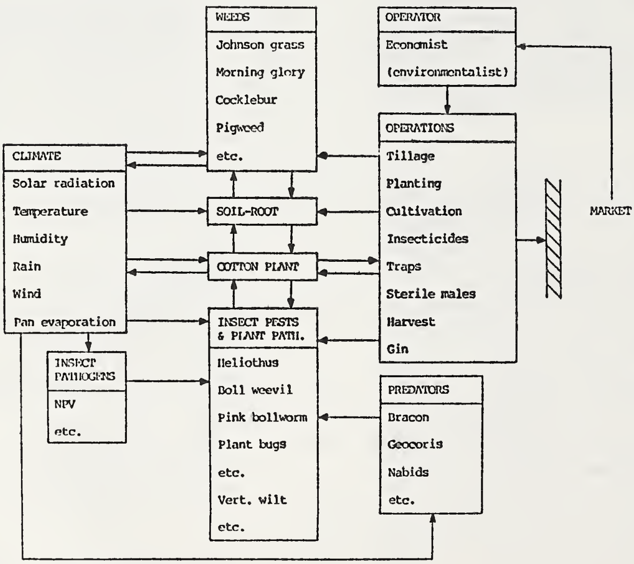


Figure 2.--Changes in cost of computer systems.

Table 2.--The 20-years trend showing the total computer market (value of worldwide shipments by U. S. manufacturers). Microcomputers will increase their market share by approximately 50 percent [1]

Market year	Market value	Types of Computers and % of Market				
		Main-frame	Mini	Small business computer	Word Processing	Micro
1975	13 Bil.	83	10	3	4	0
1980	29 Bil.	60	17	11	6	6
1985	63 Bil.	36	21	13	10	20
1990	141 Bil.	17	21	12	13	37
1995	313 Bil.	6	16	9	14	55

[1] Finkler, 1983.



The cotton production system.

Figure 3.--Elements of the cotton production system.

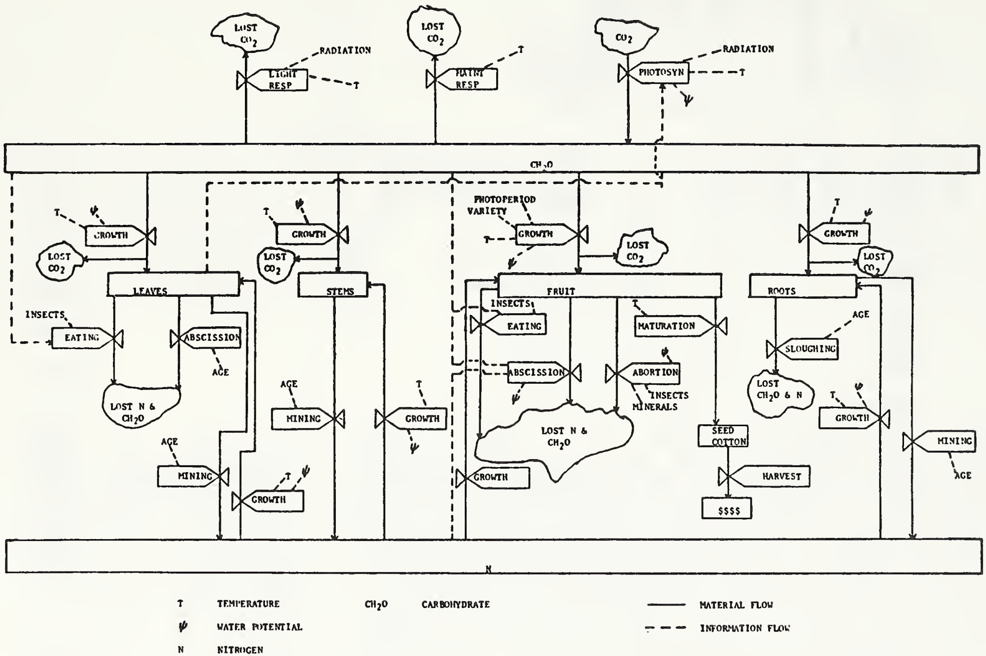


Figure 4.--The flows of dry matter and nitrogen in the cotton plant. Valve shaped structures processes. Irregularly shaped structures represent pools of undefined size. Rectangular enclosures represent pools of known size. Materials flow along solid lines. Information flows along dotted lines.

MODEL STRUCTURE

The plant and soil processes are often laid out in a subroutine structure, as shown in Figure 5. Other papers in this proceedings, by Drs. Huck, Whisler, and Cole, go into parts of this in considerable detail. In the models of Dr. Whisler et al. (1982) and others of our group, the subroutines dealing with below ground processes, including root growth, are collectively referred to as RHIZOS. They include GRAFLO, which distributes rainfall and irrigation inputs vertically in the soil profile; ET, which estimates soil evaporation and transpiration; UPTAKE which removes soil water from appropriate locations in the soil profile; and CAPFLO, which redistributes soil water. These below-ground subroutines typically compute and model soil-moisture balance, which is used in calculating plant turgor, an increment of mineral nutrient uptake, and an estimate of the sink size for metabolites in the root system. Thus, our models maintain a continuous record of water content, root biomass, and mineral nutrient content in each cell of a two-dimensional soil matrix. With the RHIZOS information available, photosynthesis and respiration rates can be calculated. The available photosynthate is partitioned to various plant parts in the subroutine GROWTH, while nitrogen is allocated in NITRO. Thus, the dry weight and nitrogen content of each plant part is updated with each model iteration. Our modeling strategy is to characterize potential organ growth and plant development rates under conditions of no physiological stress (that is high atmospheric carbon dioxide and abundant water and fertilizer) and then to apply reduction factors which are developed in subsequent controlled environment experiments.

The processes of organ initiation and abortion are usually handled as discrete events in a subroutine, for example, PLTMAP. In some models, this is simply a phenological record based on weather inputs. In our models, physiological stresses estimated from metabolite source:sink imbalances in the system result in developmental delays and/or in the abortion of plant parts.

An example of model output (from our GOSSYM model) is presented in table 3. Lines 3 and 4 present the soil water balance information, including the cumulative amounts of soil evaporation, transpiration and runoff or soak through. Lines 5 and 6 present the current dry weights of each of the classes of organs. Lines

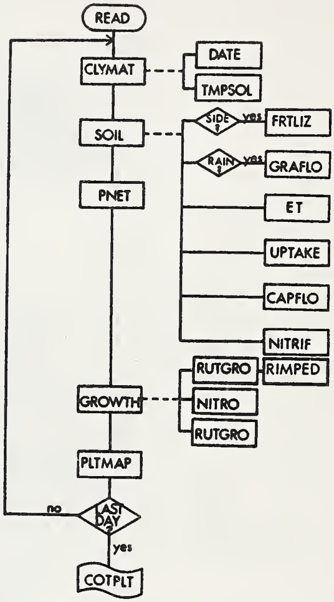


Figure 5.--Subroutine structure of the cotton simulation model GOSSYM.

Table 3. Typical Output

```
  DAY     DATE    CSTRES  NSTRES  WSTRSD  WSTRSN    TNNO3   TNNH4
  100   8-16-74  0.246       1     0.768   0.874   171.00    8.85
  TH2O    CUMRAN   CAPUP   CUMES   CUMEP   CUMSOE  H2OBAL    LAI
 212.06    55.78   19.20   31.37  135.48    0.48   284.43    3.44
  HEIGHT  WEIGHT  LEAFWT  STEMWT  ROOTWT  SQABWT  GBOLWT   DEADWT  XTRAC
 118.56  152.837  56.162  14.684  38.819   1.254  28.035   18.931  13.482

        X-I
          I-X
        X-I
          I-O
        X-I
          I-X
      X-X-I
          I-*-X
      X-*-I
          I-*-X
    X-X-*-I
          I-*-*-*-X
  X-X-*-*-I
          I-O-O-*-X             I-X
X-X-*-O-O-I                   X-I                   X-I
          I-*-O-*-X-X           I-X                   I-X
X-*-*-O-*-I                 O-*-I                   X-I
          I-*-O-*-*-X           I-*-O-X               I-*-O
O-*-O-O-*-I             X-*-O-*-I               X-O-*-I
          I-O-*-O-*-*           I-O-*-*-*-X           I-*-*-*-X
          I                     I                     I
          I                     I                     I
          I                     I                     I

      VOLUMETRIC NITRATE CONTENT OF SOIL                      DAY 100
      AT THE END OF RAIN

      UNITS -  MG/N PER CM**3                                 LEGEND

                        1 1 1 1 1 1 1 1 1 1 2
      1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0                        <=   0.0000

                                                         0.0000 < 0 <=   0.0100
  1   0       0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 0
  2   1 2 * 1 2 2 4 6 6 8 4 7 5 4 2 2 1 1 1 1            0.0100 < 1 <=   0.0200
  3   2 * * 2 3 3 4 4 4 5 4 5 4 4 3 3 2 2 2 1
  4   2 8 * 2 3 3 3 3 4 4 3 4 3 3 3 3 2 2 2 2            0.0200 < 2 <=   0.0300
  5   1 2 * 1 1 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
  6   0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0            0.0300 < 3 <=   0.0400
  7   0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  8   0 0 0 0 0 0 0 0 0 0 0 0 0                          0.0400 < 4 <=   0.0500
  9
 10                                                      0.0500 < 5 <=   0.0400
 11
 12                                                      0.0800 < 8 <=   0.0700
 13
 14                                                      0.0700 < 7 <=   0.0600
 15
 16                                                      0.0800 < 8 <=   0.0900
 17
 18                                                      0.0900 < 9 <=   0.1000
 19
 20                                                      0.1000 < *

      TOTAL =     171.0041  MG N


      ROOTS IN EACH CELL, TOT'.                               DAY 100
          AT THE END OF RUTGRO

      UNITS - G/CM**3 SOIL                                   LEGEND

                        1 1 . 1 1 1 1 1 1 1 2
      1 2 3 4 5 4 7 8 9 0 1 2 3 4 5 8 7 8 9 0                        <=   0.0000

                                                         0.0000 < 0 <=   0.0001
  1   2 2 2 1 1 1 0 0
  2   2 2 2 2 2 2 2 1 1 0                                0.0001 < 1 <=   0.0005
  3   3 3 3 3 2 2 2 2 1 1 0
  4   4 4 4 4 3 2 2 2 2 1 0 0                            0.0005 < 2 <=   0.0050
  5   5 5 5 4 4 3 2 2 2 1 0 0
  6   8 8 6 5 4 3 2 2 2 1 0                              0.0050 < 3 <=   0.0100
  7   8 7 8 5 4 3 2 2 2 1 0
  8   7 7 8 5 4 3 2 2 2 1 0                              0.0100 < 4 <=   0.0150
  9   7 7 8 5 4 3 2 2 1 1 0
 10   6 6 8 4 3 2 2 2 1 0 0                              0.0150 < 5 <=   0.0200
 11   5 5 4 3 3 2 2 2 1 0
 12   5 4 3 3 2 2 2 1 0 6                                6.0200 < 8 <=   0.0250
 13   4 4 3 2 2 2 1 1 0
 14   3 3 2 2 2 1 1 6 0                                  0.6250 < 7 <=   0.0300
 15   3 2 2 2 2 1 0 0
 16   2 2 2 2 1 0 0                                      0.0300 < 6 <=   0.0350
 17   2 2 2 1 1 0
 18   2 2 1 1 6                                          0.0350 < 9 <=   0.0400
 19   1 1 1 0
 20   1 1 0 0                                            0.0460 < *

      TOTAL =       0.9031  GM. DRY WEIGHT

  DAY SITES  SQS2   GBS     OBS    ABS MAINODES HEIGHT  LAI PSTRES  PSIAVG
  100   87  30.74  31.49   0.00   0.22   26     116.98  3.44  0.25   -0.65
  101   67  30.49  32.37   0.00   0.55   26     117.67  3.47  6.33   -0.21
  102   69  30.14  33.01   0.60   1.71   21     116.26  3.48  0.26   -0.22
  103   89  28.61  33.49   0.00   1.63   21     115.88  3.50  0.22   -0.24
  104   94  30.89  32.37   0.00   1.14   21     120.95  3.53  0.30   -0.29
  105   94  27.84  35.95   0.00   1.84   21     121.72  3.55  0.23   -0.31
```

8 to 30 present a map of the plant showing branch structure and fruiting sites. The status of each fruit whether aborted, bloomed, or mature is also shown. Lines 31 to 94 present two-dimensional diagrams of root dry matter and nitrogen in the soil matrix. The remaining lines list part of a table of daily numbers of fruiting sites, squares, green bolls, open bolls, mainstem nodes, plant height, LAI (and index of physiological stress, total nitrate and ammonium N in the soil profile), average soil suction in the rooted portion of the soil profile and soil matric potential at 10 inches.

VALIDATION

Not many crop simulation models have been extensively validated, as yet. We have validated the cotton model GOSSYM against 61 crop years of data from several locations. The data in figure 6 are typical validation results obtained by Marani and Baker (1981). In these seasonal time courses, the circles represent field observations and the solid lines represent model predictions. We will continue to collect validation data for some time to come. We are currently working with data from the Texas High Plains.

DATA NEEDS

Crop modeling efforts of this type require several kinds of data. Obviously, field validation data for each of the model output variables is needed. Required input data nearly always include class A weather station data plus daily total solar radiation. Initial soil information includes slope, residual N, and a vertical description of soil physical characteristics, including bulk density and desorption data. We hope this workshop will help us to develop ways to obtain these initial soil data from existing archives. Required data on cultural inputs include cultivar, planting date, row width, and fertilizer and irrigation application dates and rates. Most models require time vectors for any insect and disease damage.

APPLICATION

Our crop simulation models are comparatively comprehensive. However, for the past 7 years we have done all of our developmental work on minicomputers. We can simulate a season's crop growth in a matter of minutes using several of the micros available today. Applications include large area yield forecasting, farm management decision making, breeding feasibility studies, and a number of analytical studies. Farmer inputs which can be evaluated include the planting decisions, cultivar selection, date of planting, row spacing, plant population, along with timing and amounts of fertilizer and water inputs, tillage, cultivation and drainage, and pest management strategy. The farmer now has the

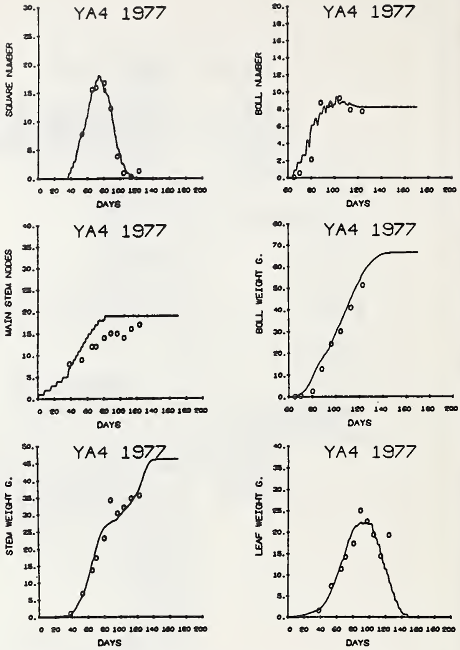


Figure 6.--Typical validation results of the Acala form of the cotton simulation model GOSSYM. Solid lines represent model predictions. Circles represent

capability to evaluate these inputs in combination. We have used our models in a number of analytical applications including a number of environmental impact assessments, and we are just now beginning to examine the beltwide yield decline phenomenon in cotton (c.f. Meredith 1982).

SUMMARY

There are several different kinds of crop models. Statistical and phenological models are often useful for yield forecasting, especially if the data base is adequate to avoid extrapolation. Development of process oriented crop simulation models dates back to 1969 (c.f. Stapleton 1970). Still, there are relatively few crop

physiologists involved in simulation. Those not involved fall into two categories: the scientist who claims the system is so simple he can handle, in his head, the problem of predicting its behavior and the scientist who claims the system is so complex that simulation is not feasible. It is not unusual for a crop scientist to take both positions in the course of a given argument over modeling.

Simulation models of about 12 crop species are available. They vary in the physical and physiological processes treated, the extent of validation work, and the consultative support available.

Hardware costs are falling dramatically, and crop simulation models are moving to the farm along with fertigation and other advanced management practices.

Most crop simulation models require input data which can be acquired at reasonable cost.

Simulation models can readily accomodate new scientific information as it becomes available, and their range of application in the areas of crop production research and management is unlimited.

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AN OVERVIEW OF ROOT GROWTH, DISTRIBUTION AND FUNCTION FOR MODELERS OF SOIL-PLANT SYSTEMS

Morris G. Huck[1]

Plant growth depends on availability of adequate supplies of water and nutrients from the soil and upon their timely uptake by the root system. To obtain sufficient amounts of water and minerals from the soil, root systems have evolved with a very large surface:mass ratio (Epstein 1973). Water and nutrients move into the roots from surrounding soil, while roots can also grow into new soil regions to exploit water and nutrient reserves stored there. Because the rate of movement of ions and water through the soil matrix toward a stationary segment of root is often slower than the observed extension rate of a root tip (Taylor and Klepper 1978), penetration of finely divided rootlets into new soil regions can be a significant factor in the spatial distribution of a living root system at any given time. The root distribution pattern of a plant at any given time may be represented as the sum of new roots formed minus those which have died at each point along a space/time continuum. Temperature, mechanical resistance, aeration, and chemical composition of the soil solution influence root growth and the exploitation of the soil volume (Pearson et al. 1970; Taylor et al. 1972). Roots compete with each other for carbohydrates, and those occupying soil regions with favorable environmental conditions tend to grow at the expense of others (Huck and Hillel 1983). When the roots are providing sufficient water for rapid growth of the shoot, available carbohydrates from photosynthetic reactions will largely be used to expand the area of photosynthetic tissues, while the roots will grow very slowly. As water stress increases, leaf growth is reduced while additional carbohydrates become available for translocation to the root system. The net effect is that of a feedback loop which tends to keep shoot and root growth in balance.

If both geometric distribution of roots and water potential distribution throughout the soil profile are known, water uptake can be calculated from catenary flow equations describing the movement of any fluid through a resistive medium (Philip 1966). Hydraulic conductivity of a soil is exponentially related to its water content, giving rise to sharp discontinuities called wetting fronts as water moves into a dry soil. A similar drying pattern can occur around individual roots when water flux rate across the root-soil boundary exceeds a critical velocity, causing local rhizosphere resistance to become so high that the flow rate cannot be sustained (Lang and Gardner 1970). Several numeric simulation models, including some presented at this symposium, describe these phenomena by internally consistent sets of equations.

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ROOT INITIATION AND LONGITUDINAL GROWTH

The biological mechanism for the advance of a growing root tip has been reviewed at length by several authors (Street 1966; Torrey and Clark 1975; Russell 1977; Kutschera 1982). Figure 1 illustrates the advance of a cotton root tip through the soil matrix. The young branch-rootlet has recently emerged from an older segment of this cotton root. At the tip of the branch rootlet is a conical section called the root cap which protects the meristematic cells in the region of cell division immediately behind. A description of the force vectors involved in the advance of a root through its environment can be inferred from the photographic studies of List (1969) and Salamon et al. (1972). Green (1968), Taylor and Ratliff (1969b), and Green et al. (1971) have discussed the nature and origin of the forces that push the root cap through the soil. Most of the expansion occurs in the region of cell elongation immediately behind the meristematic region (Esau 1965). The root tip appears to extend largely as a result of an increase in cellular volume as water flows into the vacuoles along an osmotic gradient induced by ion-pumping mechanisms similar to those which transport ions in other biological systems (Stein 1967). Protoplasm volume remains relatively constant after cells leave the meristematic region; most of the cell expansion in the region of elongation is due to an increase in vacuolar volume.

MATURATION AND RADIAL GROWTH

Diameter growth of primary root tissue is also essentially completed by the time cells have advanced beyond the region of elongation (Hackett 1973). A secondary cambium may become active in dicotyledonous plants several days after the tissue is initially laid down, but there appears to be little radial expansion of primary root tissue once the root tip has passed a given point in its soil matrix.

After longitudinal expansion of newly laid-down cells is complete, the cells are said to be in the region of maturation (Esau 1965). Histologic sections from this region show young cells differentiating into such specialized forms as conducting tissue, stele, or parenchyma. Xylem vessels are developing about 1 to 2 cm behind the growing point shown in figure 1. The beginnings of root hair formation can be seen as protuberances from epidermal cells. The region of cell maturation shown in figure 1 was laid down as the meristematic tissue passed through this same spot in the soil approximately 18 h before this photograph was taken. Typical maturation sequences such as those shown here have been documented on several occasions by cinematographic studies at high magnification (Huck 1979).

The rate at which an individual cell progresses from meristematic tissue into the cell maturation region varies markedly with temperature and with species but is relatively unaffected by mechanical

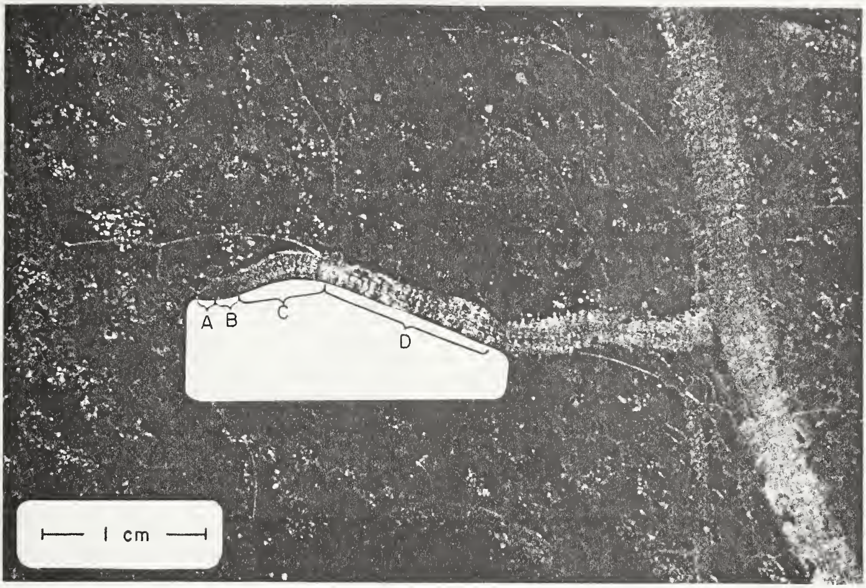

Figure 1. A lateral feeder rootlet has recently emerged from a larger secondary root of cotton. Root cap (A), meristematic region (B), cell elongation region (C), and region of maturation (D) with extensive root hair development can be seen in the lateral. The length of this rootlet has increased by approximately 2 cm during the past 24 h. Numerous fungal hyphae are visible in the wet soil behind this glass window.

resistance of the soil. Thus, tissue aging is the variable which a descriptive model must consider. Because their growing tips penetrate the soil volume more slowly, roots growing in high-strength soils tend to be shorter, with less separation between the meristematic region and the maturation zone than roots growing in looser soils. Cellular maturation, the common variable, occurs at a rate determined by temperature and genetics of the plant, while linear advance of the root cap slows under more difficult growing conditions. Thus, the morphology of roots growing in high-strength soils is quite different from that of those grown in loose soils, as pointed out by Camp and Lund (1968).

As the developing root tissue advances into the region of maturation, xylem and phloem elements differentiate and the root segment begins to function as an active absorbing organ (Truog 1922, Russell 1971). Water and minerals move from the surrounding soil microenvironment into an adjacent root segment and then to other organs of the plant by a highly efficient network of conducting tissue (Burch et al. 1978). Dynamics of mineral uptake processes have been discussed elsewhere (Passioura and Frere 1967; Clarkson et al. 1971) and in this symposium.

Rootlets generally show signs of senility after a period of active functioning, the duration varying with species and environment. Root hairs are lost and cortical tissue discolors and sloughs. A root segment that is a part of a contiguous conduction system leading from the shoot to an active root tip or cluster of tips will probably remain in place and continue to function as a pathway for long-distance transport. Secondary cambial activity causes radial expansion of mainline roots of dicotyledonous plants within a few days after the cells have differentiated. On the other hand, if growing tips at the distal end of a root segment are not in a favorable soil region, they will not be able to obtain water and minerals, and all that segment of root up to the branch point from the next higher order main root will generally cease to function.

The plant will tend to favor other root tips growing in more favorable soil regions. As secondary cambial growth increases root diameter, the radial path from soil to root xylem elements becomes longer and epidermal tissues are less permeable with age. Thus, the function of active absorption of water and minerals is gradually relegated to younger rootlets. Older roots either die, or else they initiate new branches which can explore new soil regions from which water and nutrients can be extracted.

THE COMBINATION OF INDIVIDUAL ROOTLETS INTO A ROOT SYSTEM

On any plant growing under natural conditions, many root tips are simultaneously advancing into the soil matrix and competing for food reserves (Hackett and Rose 1972). Individual root tips behave as any other assembly of living things competing for scarce elements (de Wit, 1960). When the 5- to 15-day active life span of individual feeder rootlets is completed, these older rootlets begin to die as they exhaust available resources in their immediate vicinity. New feeder rootlets are being formed during most of the active life of the plant, although the rate of new root initiation is reduced at flowering and again during senescence (Huck et al., in preparation). Thus, the total root system supporting a plant at any given time represents a dynamic equilibrium between the formation of new rootlets and the dying of old ones.

In our rhizotron studies, rotting is seldom seen on a functioning root of any species but proceeds quite rapidly after the root tip ceases elongation. A nonfunctioning cotton or soybean rootlet may completely disintegrate within 2 to 3 weeks after initiation. Rotting rate depends largely upon soil temperature and aeration, being quite rapid in warm soils with good aeration but very slow during the cooler seasons of the year when many soil pore spaces are filled with water. By comparison with roots of dicotyledonous plants, grass roots appear surprisingly resistant to rotting, often remaining visible at the viewing surface for several months after initiation.

The concept of biomass partitioning between young, functional roots and older roots growing in other soil regions is similar to that underlying the mathematical descriptions of organisms in ecosystems (Kline 1973; Parton and Marshall 1973). Root tips grow faster in a favorable soil environment, accumulating biomass more rapidly and developing more branch points. Thus, the net effect, when averaged over time, is that more of the total root system will grow into the favorable soil environment. Root biomass distribution becomes a kind of self-correcting system, with the most rapid growth into the most favorable soil region accessible to the plant. Individual roots in less favorable regions die back and are replaced slowly, if at all. As moisture distribution, temperature regimes, and other environmental factors change during a growing season, the active root system will appear to track the soil region that is more favorable for root growth at any given time (Kutschera 1982). As successive rains cause the surface layers to be alternately favorable and unfavorable, successive generations of roots on the same plant may alternate between surface layers and deeper soil layers.

EXPERIMENTAL APPROACHES TO THE STUDY OF ROOT GROWTH

Single-root Experiments

The interrelationships of microenvironmental parameters which influence the dynamic equilibrium between the growth of new roots and the decay of older ones can sometimes be inferred from constant-environment experiments in which new root growth is measured as a function of a single environmental parameter. In such experiments, the formation and growth rate of new root tips depend upon measurable factors in the environment, as well as upon the genetic background, age, and flowering behavior of the plant. Some tentative conclusions can be drawn from studies conducted at Auburn, AL, involving radicle extension rate of cotton seedlings growing along a glass window in a sealed box filled with moist soil (Pearson et al. 1970, Taylor et al. 1972). Food reserves stored in the cotyledonary endosperm of germinating seeds provide an abundant supply of carbohydrate for root growth. Because the glass-sided boxes in these experiments were sealed and kept at a constant temperature, perturbations of the system by variation in water content, water movement, or drying of any particular soil region were eliminated. Thus, growth of these root tips, under constant environmental conditions with a uniform soil, depended only upon the experimental soil treatments imposed and the genetic makeup of the seed. After the radicle emerged from the seedcoat, its extension rate was linear until formation of lateral branches, when linear growth of the terminal meristem declined (fig. 2a). Genetic variation between replicate experiments was controlled by use of carefully selected inbred seed lines so that plant responses to environmental variables could be observed.

Chemical composition of the soil solution (Pearson 1971) also affects radicle extension rate profoundly. One example of this response is the relationship between radicle extension and specific ion activities (Adams and Lund 1966, Lund 1970). As shown in figures 2b and 2c, which are based on data from the experiments of Pearson et al. (1970), growth response to toxic levels of trivalent aluminum ion induced by excessive soil acidity assumes the same exponential form as a chemical reaction described by the law of mass action (Moore 1962). Although the internal reactions within the root tissue resulting from exposure to toxic levels of aluminum may be quite complex (Huck 1972; Matsumoto 1980), the observed relationship between root extension rate and solution aluminum activity can be expressed by relatively simple regression equations for predictive use in models describing root growth under varying soil conditions.

Root growth response to variation in mechanical resistance of the soil is quite marked, even at relatively low levels of soil resistance (fig. 2c and 2d, from data of Pearson et al. 1970). This relationship between soil strength and root

Figure 2. Taproot elongation of cotton seedlings as a function of several interacting independent variables from data of Pearson et al. (1970). The combined results of 877 independent sets of obervations in more than 100 separate experiments were combined for multivarient analysis. A 27-term polynomial fitting all available data with R^2 >0.85 was solved for combination of independent variables plotted here. "Pressure" units refer to resistance encountered by a cone penetrometer and are thus a measure of the mechanical resistance of the soil.

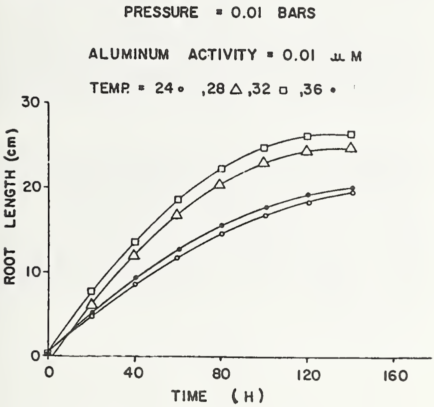

Figure 2a. Taproot elongation rate vs time, using emergence of the radicle from the seed coat as time = 0. After the initial delay for seed hydration and mobilization of stored food reserves, the cotton taproot extends at a fairly constant rate until the growing point encounters an unfavorable soil environment or until lateral branches begin to appear and compete for food reserves.

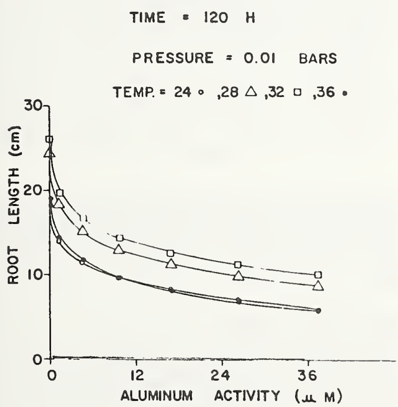

Figure 2b. Taproot length as a function of trivalent Al+++ activity expressed as Al+++ concentration; obtained by multiplying single ion activity coefficient obtained from Debye-Huckel approximation using the method of Kielland (1937) times its observed concentration in the soil solution extracted by the method of Pearson (1971).

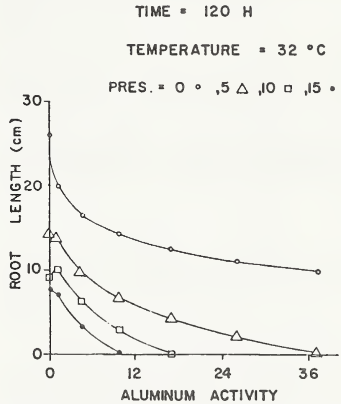

Figure 2c. Taproot elongation as a function of trivalent Al+++ activity at an optimum temperature. Under conditions of moderate soil resistance, small amounts of Al+++ are evidently beneficial to the root system, perhaps lessening the chemical activity of other ionic species which may be present at excessive concentrations. When conditions of both excessive Al+++ and excessive soil strength are found in the same soil, the taproot simply fails to elongate beyond a centimeter or 2 and the seedling does not survive.

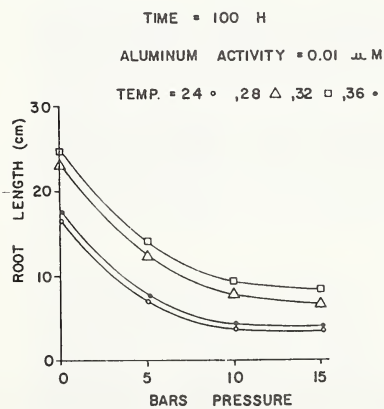

Figure 2d. Taproot length at 100 h as a function of soil strength in the absence of toxic levels of Al+++.

elongation rate is complicated by an implicit relationship between soil strength and soil water content (Camp and Lund 1968). Thus, the experimentally observed correlation between soil water content and root extension rate is often mistakenly assumed to represent a causative mechanism involving soil water as a factor controlling root growth rate.

Soil strength, however, is an intermediate variable whose value varies with soil water content as well as with other parameters, such as bulk density. Klute and Peters (1969) reported an empirical relationship between root growth rate and soil water content. Taylor and Ratliff (1969a) showed that root growth rate was independent of water stress over a range of -0.17 to -0.8 bars during the first 100 h of growth under their nontranspiring conditions. Grenetz and List (1973) described a model relating root elongation rate and external water potential, and Sharp and Davies (1979) showed that root extension was less sensitive to water stress than shoot expansion. Total plant growth versus soil water availability is the relationship more commonly reported in agronomic literature. Arbitrarily measured or estimated soil density and mechanical composition data may occasionally be supplied; a rough estimate of soil strength may be obtained from data of this nature in some cases (Camp and Gill 1969).

Under nutrient solution conditions, root growth rate is generally much higher than in soils where the root tip will encounter mechanical resistance to its extension. Thus, the controlling factor limiting root growth rate under natural conditions is soil strength, often in combination with an unfavorable chemical environment. The interactive effects are of more statistical significance than the primary effects (unpublished data, Huck et al.)

Huck (1969) showed that cotton seedling root extension cannot occur without a molecular oxygen supply. Diffusion of gases to and from the respiring root tissue can take place internally between shoot and root (Luxmoore et al. 1970), but in pea seedlings this pathway was of minor importance compared with diffusion through the soil (Eavis et al. 1971). Although the longitudinal diffusivity of air-filled pore spaces within roots is often substantial, the interface area between the end of these channels and the tightly packed respiring cells in the root tip is very small.

In the soil, gas diffusivity through air-filled soil pores increases at increasing air-filled porosity. Because water and air compete for the same pore spaces within the soil matrix, gaseous diffusivity must decrease as soil water content increases (Melhuish et al. 1974). Living roots are surrounded by films of liquid soil water; thus the diffusion path for gaseous diffusion between gas-filled pores and the respiring root includes a liquid phase. The influence of different spatial arrangements of solid, water, and gas phases around root tips and their effect on equilibrium oxygen concentration at root surfaces were determined empirically by calibrating seedling radicle extension rates in well-aerated soils of equivalent mechanical impedance bathed in gases of different oxygen concentrations (Eavis 1972). Reduction of both mechanical and oxygen stresses at the same time resulted in greater elongation rates than when each factor was reduced independently. The growth pressures which root tips could generate against a mechanical resistance were independent of oxygen concentration down to 3 percent in peas, but were reduced at oxygen concentration of 3 to 8 percent in cotton (Eavis et al. 1969).

Hilton and Mason (1971) reported both light and temperature effects on root growth rates. Radicle elongation rate in controlled growth room experiments in Alabama responded to temperature variation in a characteristic manner (fig. 2e), which resembles a typical enzyme-kinetic curve. Under field conditions, temperature of the surface layers containing most of the active root system varies markedly with time, tillage and many other factors (Gupta et al. 1983).

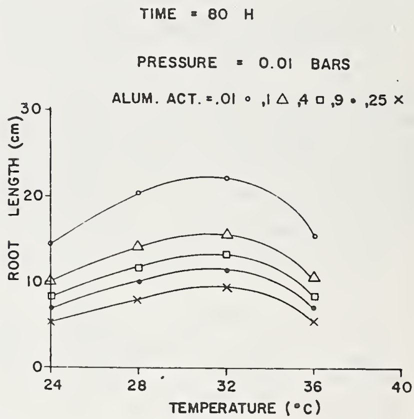

Figure 2e. Influence of temperature upon elongation of cotton taproots in very loose soil. The optimum growth of this warm-season crop evidently occurs near 32°C, with an abrupt decline in growth rate if the soil is held at a constant 36°C.

Field Investigations

Most field investigations of root distribution (Weaver 1926, Kutschera 1960, Portas 1970, Kolesnikov 1971, Schuurman and Goedewaagan 1971) have been based on data obtained by destructive excavation and direct observation of root systems as they existed when excavated. The implanted soil mass technique (Gardner and Telfair 1954, Telfair et al. 1957, Lund et al. 1970) permits studies of root penetration in a horizontal direction across a boundary between two dissimilar soils. Information concerning the dynamic behavior of the soil-plant system is extremely difficult to obtain from isolated single-observation

studies of this nature; however, Bohm (1979) has summarized various methods for obtaining quantitative estimates of root distribution by selective sampling techniques applicable to field-grown roots.

Several specialized laboratories have been constructed in recent years which facilitate observations of the dynamic behavior of plant root systems under natural conditions (Rogers 1969, Hilton et al. 1969, Huck and Taylor 1982). Plants are grown outdoors for several months or longer, with their roots permeating a natural or simulated soil profile. In these laboratories, intact, growing root systems can be observed through glass windows which support the soil in large compartments. The soil of each compartment has a known physical and chemical composition, and roots in these soils grow at a rate controlled by the genetic composition of the plant and by the nature of the microclimate to which the plant and its individual roots are exposed.

While temperature, water content, and other time-variant soil properties cannot easily be controlled, they are generally monitored by sensors attached to a data acquisition system. The resulting observations can be sorted by digital computer into classes or sets of observations and arranged to form appropriate combinations over a range of each dynamically varying soil property. Response surfaces can be computed by regressing root growth on various soil or microclimatic properties using short-term variation randomly introduced into the system by its exposure to the elements of nature, and then sorted by class variable before statistical analysis. With more complex units, such as that described by McKinion (1980), one or more environmental factors can be deliberately varied by the experimenter, either during the growing period or when the treatments are installed. Root growth rate, the dependent variable, is obtained by comparing sequential photographs of the same root system or by noting differences in total measured root length (Taylor et al. 1970, Browning et al. 1975), in successive observations.

In the simplest case, only the total number of roots or the total root length per unit viewing surface at each depth and time of observation is recorded. This total root length data, however, cannot clearly differentiate between a static root system and one in which the rate of new root formation exactly equals the decay rate of older rootlets. Studies have been made involving maintenance of identity for individual rootlets (Huck et al., in preparation), which permit calculating daily growth increments of an average root and its mean life expectancy. Distinguishing between active and inactive segments of a live root system (Nakayama and Van Bavel 1963) is still an arbitrary process, although Karnok and Kucharski (1979) suggested that ultraviolet fluorescence may be a useful criterion for distinguishing live roots from dead tissue.

The line-transect method of Taylor et al. (1970) has been widely used as a rapid means to estimate rooting density as a function of depth within a soil profile. This method is illustrated in figure 3, which shows a corn root system growing in soil behind a glass window containing a wire grid. Intersections between the 30-cm transect line and the root system are marked with white arrows. By counting the number of intersections between roots and the transect line, the length of root per unit viewing surface can be estimated. A new regression equation comparable to that given by Taylor et al.(1970) must be developed for each experimental situation because of the anisotropy considerations discussed by Lang and Melhuish (1970). The empirical regression determined for each new species to which this technique is applied will vary because of the different angular branching habits of the roots of different species (Melhuish et al., personal communication).

It is generally possible to estimate the distance behind the window to which roots are visible by microscopy at high magnification (which results in a very limited depth of field). By careful adjustment of the microscope focus knob, one can measure the distance between the inner surface of the glass window and a parallel plane representing the deepest recess at which roots are visible within the soil matrix. Using this distance as a multiplier, the root length per unit viewing surface (cm/cm^2) can be converted to root length per unit soil volume (cm root/cm^3 soil volume). This conversion, of course, involves an implicit assumption that the roots are uniformly distributed in the horizontal planes which intersect the window, so visual estimates must be checked by destructive sampling at periodic intervals to provide estimates of measurement error.

Estimates of average root length per unit soil volume are useful for calculations involving flow of water or minerals across the root-soil interface, but other studies such as those of May et al. (1967), York and Sagar (1970), or Hackett and Rose (1972) require information concerning contiguity of primary, secondary, and higher order branch roots. For such experiments, determining the average rooting density is less important than obtaining a comprehensive map of the contiguous pathways from root tip to the shoot. In these cases, the rhizotron viewing window should be inclined at an angle of about 10° to 15° from the vertical so that geotropism will encourage roots to grow directly along the glass surface. Root density at the glass will then be higher than that measured in bulk soil, because additional roots will tend to intercept the glass as they grow downward.

WATER MOVEMENT AND UPTAKE PATTERNS

In most natural systems water is supplied to the soil surface by rainfall or irrigation. It then flows into and through the soil system behind a wetting front (Green and Ampt 1911). As the soil becomes progressively wetter, its conductivity increases, so the tendency toward sharp discontinuities of water content is self-reinforcing. Hillel (1980) has given a comprehensive description of the way in which water moves through a soil profile as its surface and sub-

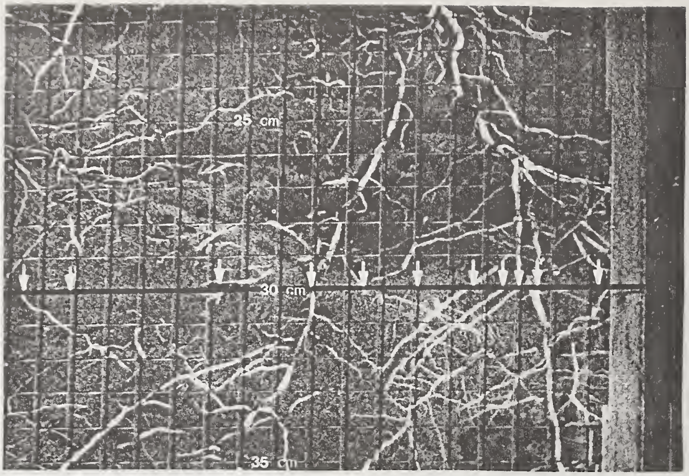

Figure 3. Section of a corn root system as seen through a rhizotron window. The wire grid embedded in the window is spaced at 1/2-inch (1.27 cm) intervals to form a stable reference for precise location of roots. Arrows indicate points at which a visible roolet intersects the 30-cm transect line (see text).

sequently deeper layers are alternately wetted by rainfall or irrigation and then dried by evaporation or plant uptake.

The geometric pattern of water removal from the root zone differs markedly from the wetting pattern (Buckingham 1907). When soil water content is above saturation, films of liquid water will drain from the surface to the subsoil or groundwater (Miller and Aarstad 1972). Surface evaporation can occur initially, but after a crust of dry soil forms and retards moisture conductivity, this process becomes very slow (Van Keulen and Van Beek 1971). Ritchie (1972) demonstrated a numeric solution to a system of equations describing water movement in an agricultural soil and tested the predictions of his model against measurement data; other more complex solutions are presented elsewhere in this symposium.

In moist soil, roots remove water according to the needs of the plant and their location (Huck and Hillel 1983, Klepper et al. 1973). As wetting and drying fronts alternately pass though a given region of soil volume, roots in the given volume element will be exposed to rather different microenvironments. Because soil water distribution in the soil profile changes when rainfall or irrigation wets the soil, the portion of the total plant root system which can most effectively obtain water from its immediately surrounding soil volume will vary with time and space during water removal. The drying pattern is not at all congruent with the wetting pattern (Taylor and Klepper 1971).

Because the nutrient composition of the soil solution also changes with time (Raats 1973), it is necessary to consider not only the location of both water and roots but also the dynamic concentration of major nutrient elements in the soil volume being explored (Parr 1973). Schuurman (1971) showed that restricting the soil volume which a root system can explore need not reduce plant growth if adequate nutrients are supplied. Many mathematical models have been proposed for calculating ion movement in a soil-plant system at varying water contents. Early examples are those of Passioura and Frere (1967), Tanji et al. (1967), or Rao et al. (1979) More recent work is described elsewhere in this symposium proceedings.

PREDICTION OF ROOT GROWTH PATTERNS

The requirement that roots constantly extend into unexplored regions of the soil to insure a supply of water places a heavy demand for carbohydrate food materials upon the plant. As a result, there is intense competition between each component of the root system and storage organs of the shoot. A theoretical basis for partitioning food reserves between competing plant compartments was given by Thornley (1972). A numeric model incorporating this concept of a dynamic equilibrium between the shoot and several competing root subsystems (Wareing 1972) was developed and reported by Huck et al. (1975). This model used the photosynthetic system of DeWit et al. (1970).

The experiments of Brouwer (1954), as interpreted by the simulation studies of Brouwer and DeWit (1969), illustrate a basic principle involved in the relationship between shoot and root growth. Their studies, as well as our own simulation efforts (Huck et al. 1975), suggested that for

each given combination of species and environmental factors, there exists an optimum relationship between shoot size and root size. Perturbations from an equilibrium growth situation induced by pruning either shoot or roots (Stansell et al. 1974) will result in a rapid return to the equilibrium shoot:root ratio, because the pruned plant organ grows at the expense of the surviving organs. If a shoot:root ratio is at equilibrium for a given set of environmental factors and a marked change in the microenvironment of the plant is introduced into the system (Huck et al. 1983), the plant will rapidly adjust toward a new equilibrium state with a new shoot:root relationship consistent with the new set of environmental demands.

The conceptual basis for partitioning biomass in these simulation studies is restricting growth of plant organs that produce growth components present in excess of the plant needs while favoring growth of those plant organs which can supply the needed components. During early stages of ontogeny, the plant is considered to be a two-compartment system with the shoot supplying carbohydrate to support growth of the entire plant and the root supplying all necessary water. If water is abundant, most of the available carbo-hydrate will go into additional leaves until eventually evapotranspiration is so high that photo-synthesis must be limited by stomatal closure due to water stress (Bierhuizen and Slayter 1964, Jordan and Ritchie 1971). As water becomes more limiting, an increasing fraction of the nonstructural carbohydrate reserves (Smith 1969) will become available for root growth (Blaser et al. 1966, Lechtenberg et al. 1973). A feedback loop to maintain a stable equilibrium between size of shoot and size of root is thus created.

In the root growth model described by Huck and Hillel (1983), as well as that of de Wit et al. (1978), growth of all plant organs is proportional to the level of available carbohydrate reserve. Growth of any plant organ is also considered to be proportional to the biomass already present in that organ or class of organs. Thus, with roots in all soil compartments competing for carbohydrates from the same photosynthetic pool, those roots in the most favorable environment grow most rapidly. In effect, the rapid growth of vigorous roots will reduce the level of food resources available for competing roots growing in less favorable soil regions. Conversely, when root growth slows due to adverse soil conditions, more carbohydrate will be available to support root growth in other soil regions with more favorable conditions, subject to the limitation that there must be at least some root tissue in an adjacent compartment to support exploration of a new soil region.

Roots are considered to grow from one soil layer into an adjacent layer at a rate proportional to the sum of root biomass in the layer of interest plus a weighting factor times root biomass in the adjacent layer. The weighting factor is analagous to a unidirectional diffusivity of root biomass into adjacent deeper soil layers, and provides a means for root entry into soil layer which contained no roots at initialization. As more and more roots grow in each soil compartment, further growth will be proportional to the biomass already present, and an exponential growth curve results.

PREDICTION OF WATER REMOVAL BY ROOT SYSTEMS

Once the distribution of roots and soil water potential through the soil profile are known, a realistic estimate of the soil water removal pattern is possible. Plant water potential can be measured (Scholander et al. 1965) or computed (Philip 1966) from a variety of subparameters considered in other sections of most simulation models. The principal impediments to the water flow from the soil into the plant are those imposed by the root epidermis and the Casparian strips surrounding the conducting tissue of the stele (Kleinendorst and Brouwer 1972, Newman 1973) and those imposed by the resistance to flow through the soil itself. Molz (1975, 1976) has reviewed the system flow characteristics and proposed some analytical solutions. In wet soil, the predominant resistance lies within the root tissue, but as water is removed, the soil contributes a much larger proportion of the total flow resistance because of the exponential relationship between hydraulic conductivity and soil water content.

If water uptake is to be averaged over a period of several days or longer, extraction models based upon diffusivity equations such as those proposed by Gardner (1964), Molz and Remson (1971), or Gardner (1973) can be useful. These models, however, cannot account for detailed changes in root distribution as a function of time, and they lack terms corresponding to individual resistance components along the flow pathway.

Extraction-term models which view roots as a uniformly distributed system throughout the soil rooting zone cannot easily consider the effects of the discontinuity at the soil-root boundary, called the rhizosphere. Kinetics of flow through the rhizosphere layer must be considered to accurately describe the time course of water removal from the soil (Jackson et al., 1973). Lang and Gardner (1970) showed that that as a root removes water from the thin layer of soil adjacent to its surface, the rhizosphere layer rapidly decreases in conductivity. The more rapidly the root removes water from its surrounding soil, the steeper the "drawn down" curve through the rhizosphere layer will become. Lambert and Penning de Vries (1973) made numeric simulation studies of the radial flux of water from bulk soil to a single straight cylindrical root and obtained data similar to that shown in figure 4. Their simulation model, called TROIKA, verifies the predictions of Lang and Gardner (1970).

As the flux of water toward each rootlet increases with greater evapotranspirational demand during the day, the water content of the rhizosphere decreases. Thus, the peak demand for water occurs at the very time of day when soil conductivity is lowest. The net effect is that the root initially removes water from the innermost region of the cylindrical shell surrounding it. As inner layers

Figure 4. Rhizosphere water potential as a function of distance from the root surface (data replotted from simulation studies of Lambert and Penning de Vries, 1973). Dash lines show position of gradient in previous plot or at initialization. Initialized with soil uniformly wet: at -0.77 bars (● ● ●), at -1.46 bars bars (o o o), and at -5.86 bars (x x x).

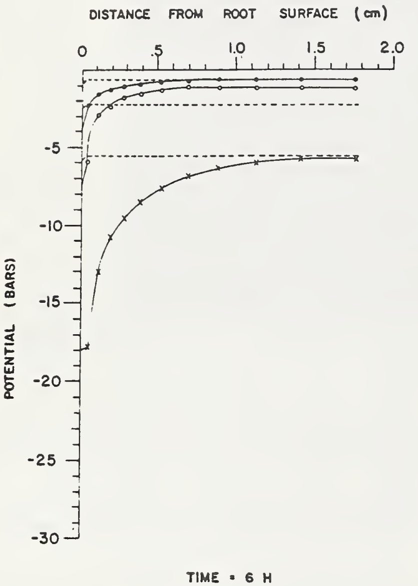

Figure 4a. Potential gradients after 6 h of transpiration.

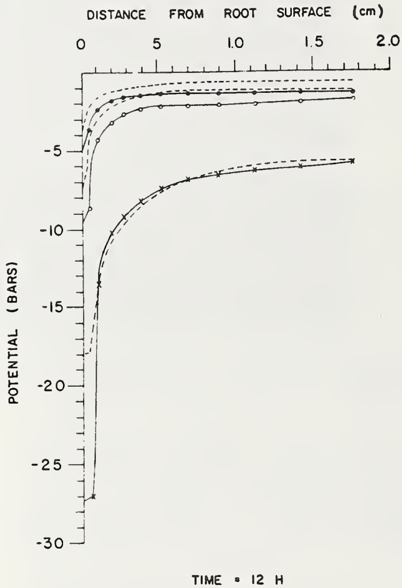

Figure 4b. Potential gradients after 12 h of transpiration. At this point, the simulation studies assumed the onset of darkness, with a marked reduction in transpiration demand by the shoot.

of the shell are dried, water must be drawn from soil at a greater distance from the root and must pass through soil having lower conductivity (fig. 4). When superimposed upon the typical diurnal variation in shoot water demand, this means that plant water potential must change significantly as the rhizosphere layer is alternately dehydrated and rewetted on a diurnal cycle. Faiz and Weatherly (1982) have presented data suggesting a loss of root-soil contact when water flux is too great. Huck et al. (1970) have shown that primary root tissue may temporarily shrink from water stress but that the magnitude of shrinkage diminishes markedly after the cells have thickened sufficiently to give the tissue mechanical rigidity. The kinetic effects of variation in flow resistance at the root-soil interface are discussed in greater detail elsewhere (Huck, 1984).

Huck and Graves (1976) extended the flow equations from TROIKA to consider a more complex root system in a heterogeneous soil. Numeric simulations with their extended version suggested that resistance to water flow across root tissue from the root epidermis to the xylem vessel is significant only in very wet soil and that the rhizosphere resistance varies markedly with the rate of water uptake and with the initial water content of the soil each morning. Longitudinal resistance. (Taylor and Klepper 1978) may be important if its value is large compared to total radial resistance Its main consequence was in influencing the relative contributions of various soil horizons to total water extraction rate. Schuurman (1982) has given an excellent summary of the relevant relationships between root functions and root growth.

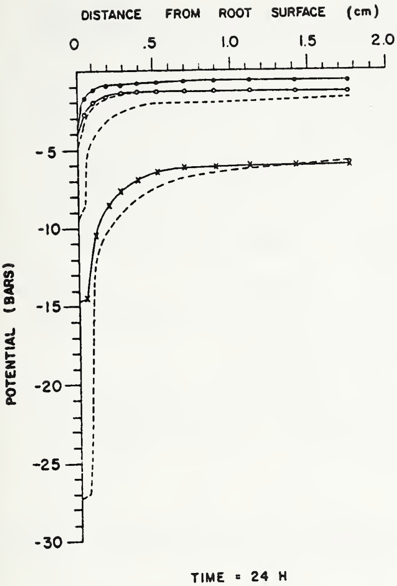

Figure 4c. Potential gradients in same soils 24 h from initialization (after 12 h or equilibration in darkness with closed stomata). The conductivity in the driest soil is so low that the root must begin its second day at a much lower potential than on the first day of simulation.

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CROPS AND SOIL SIMULATION--SCS COMMENTS

Allen R. Hidlebaugh[1]

The three speakers in this segment of the symposium have given a good overview of the state of the art in the systems approach to soils research, in crops simulation, and in modeling the growth of roots.

The Soil Conservation Service (SCS) is currently working with ARS on two modeling efforts that use crops and soil simulation. These are the Erosion Productivity Impact Calculator (EPIC) and the Productivity Index (PI) approach. EPIC will simulate the relationship of erosion to productivity for each of the eight RCA soil groups for each major land resource area (MLRA). These relationships will be used in the Center for Agricultural and Rural Development (CARD) model for the next resource appraisal required by Public Law 95-192, the Soil and Water Resource Conservation Act (RCA). SCS may also be able to evaluate existing estimated yields for given crops on specific kinds of soil. Estimated yields that differ greatly from the yields computed by the models are prime candidates for further study.

Crops and soil simulation can and will be used more extensively by SCS. We will need to have an active role in converting promising research models to operational models that will use available SCS data sets and provide data of value to SCS. These models are needed in several areas of interest to SCS, such as assessing the impact of conservation tillage on crop yields and continuing the assessment of the effects of all forms of erosion (sheet, rill and ephemeral gullies from water erosion and wind erosion) on crop yields. It is not likely that every research model of crop and soil simulation will have an operational counterpart that SCS can adapt to its programs. However, SCS will continue to support current and future research in that field.

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REMOTE SENSING APPLICATIONS TO HYDROLOGIC MODELS

Albert Rango[1]

INTRODUCTION

As evidenced by the papers presented at this symposium, the Agricultural Research Service (ARS) has undertaken a major research effort to develop a means for assessing the condition of our natural resources and management strategies for improving their quality. The approach being used involves development of models for analyzing and simulating various physical processes and recommended management options. The result of these efforts has produced a number of natural resource simulation models, the components of which seem to have a number of similarities. In addition, there are a number of similar models developed by other agencies that have not been presented at this symposium.

Most of these natural resource models are site specific to a large degree and as such require very detailed information about site geometry, physical conditions, biological properties, and state of the system. Because of these requirements, application of these models to a number of locations will require large amounts of data to be collected and analyzed.

Remote sensing can have an important role to play in increasing the efficiency of obtaining data for these models and in acquiring data useful for updating and feedback purposes. The use of remote sensing to feed information to the models should also permit application to considerably more areas than would be possible using conventional data sources alone.

Most of the experience that has been obtained with remote sensing data in the Hydrology Laboratory has been in connection with the utilization of hydrologic models. Although most of the remote sensing examples that will be presented come from hydrologic model applications, applicability to natural resource models in general and agriculture is easily seen. The potential for remote sensing applications to these areas is much greater than what has been accomplished so far. This paper is meant to assess our current remote sensing capabilities and what we could reasonably expect to result in future years.

REMOTE SENSING CAPABILITIES

Table 1 is a listing adapted from Groves and Ragan (1983) which summarizes the various hydrologically-related parameters that have been measured using existing satellite systems by different investigators. A number of remote sensing experiments have also produced research results that have shown the definite potential for obtaining additional parameters listed under future capabilities in table 1. Most of the current capabilities involve measurement of surface characteristics using visible, near infrared, and thermal infrared data. Expected future capabilities will extend measurements below the surface as a result of the penetrating characteristics of the microwave wavelengths.

In relation to the capability of inputting various remote sensing derived data, hydrologic models can be classified into three major types. Type 1 are specific situation models that already require the input of areally averaged information (like that available from remote sensing) in order to operate. Type 1 includes models that require land use information and snow-cover extent to produce discharge estimates.

Type 2 are models that in theory require the type of information available from remote sensing. When these models were first developed, however, remote sensing data were not available, and the models were adapted for using surrogate information obtained either from other data sources or from model-generated data. In order to accept remote sensing data directly now, each of these models would require modification. Type 2 includes most of the existing conventional hydrologic models.

Type 3 are new models developed to be completely compatible with remote sensing data and designed to make optimum use of the remote sensing capabilities. Otherwise, these models closely resemble the conventional hydrologic models in structure.

MODEL PERFORMANCE WITH REMOTE SENSING DATA (TYPE 1)

An interagency project compared conventional and Landsat-derived land-cover data for use in the U.S. Army Corps of Engineers HEC-1 model by evaluating discharge frequency curves produced by the model (Rango et al. 1983). When a grid-based data-management system was used on a cell-by-cell basis (cell size about 1.1 acres or 0.45 hectare), Landsat classification accuracy was on 64%, but when grid cells were aggregated into subbasins, the classification accuracy increased to about 95%. When both conventional and Landsat land-use data were input to the HEC-1 model for generating discharge frequency curves, the differences in calculated discharge were judged insignificant for subbasins as small as 1.0 mi^2 (2.59 km^2). In figure 1, for example, the Landsat and conventional approaches for Pennypack Creek show minimal differences. Figure 1 also shows the discharge frequency curves that would result if the Pennypack Creek basin were modeled using all industrial or all natural vegetation SCS curve numbers. For basins larger than 10 mi^2 (25.9 km^2), use of the Landsat approach is more cost effective than use of conventional methods (Rango et al. 1983).

It has recently been reported (Owe and Ormsby 1984) that on a basin in Georgia, cell-by-cell land-use-classification accuracy averaged 68% using Landsat MSS data, which corresponds

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Table 1.--Hydrologic parameters currently or potentially available from remote sensing

Satellite	Sensor	Physical or hydrologic data
Landsat	Thematic mapper or multispectral scanner	Land cover, impervious area, surface water extent, albedo, snow and ice cover, drainage networks, vegetation species, extent, and characteristics.
NOAA Polar Orbitor	Advanced very high resolution radiometer	Vegetation species, biomass, canopy temperature, albedo, ice and snow cover.
GOES	Visible and infrared spin scan radiometer	Cloud cover and movement, solar radiation, surface and canopy temperature, albedo, high altitude winds.
Future	Microwave or infrared	Soil moisture, snow water equivalent, precipitation, soil hydraulic properties, evapotranspiration.
Future	LIDAR	Elevations and channel cross sections.
Future	Advanced multispectral imaging system	Detailed natural and urban drainage stucture, spatial variability within drainage units.

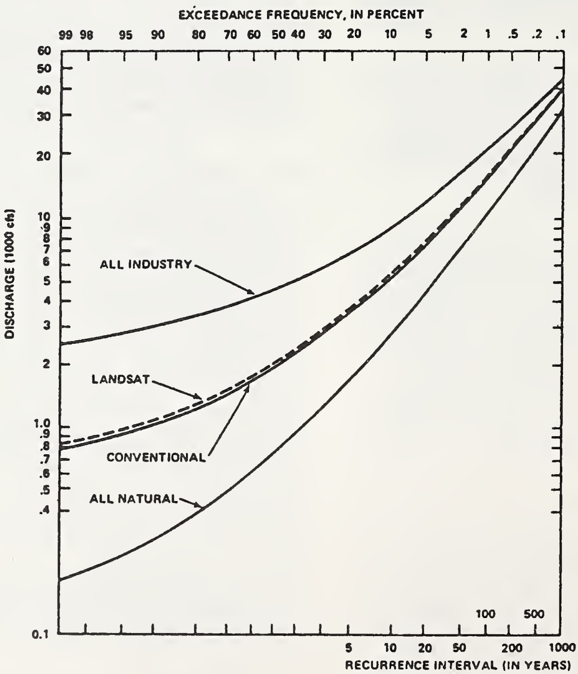

Figure 1.--Landsat and conventional discharge frequency curves generated using the HEC-1 model for the Pennypack Creek Basin (56 mi^2; 145 km^2).

closely to the results by Rango et al. (1983). Corresponding tests were run using Landsat thematic mapper (TM) 30 m resolution data. A cell-by-cell classification accuracy of 87% was obtained, indicating a strong potential for TM improving the quality of remotely sensed land cover information for modeling purposes based on improved spatial and spectral resolution.

Similar to the areal land cover information is the remote sensing capability for mapping snow-cover extent. These data can be input directly to a snowmelt-runoff model (SRM) designed for simulating and predicting snowmelt runoff from mountain basins (Martinec et al. 1983). In addition to snow-cover data obtained from satellites, the model only requires the input of daily temperature and precipitation data. For model operation, the following parameters must be predetermined: degree-day factor, runoff coefficient, recession coefficient, temperature lapse rate, and discharge time lag. The model has been tested with satellite snow-cover data on 9 large basins ranging from 228 km^2 to 4,000 km^2 in size. The average absolute error between actual and simulated runoff volume for the snowmelt season for all basins and years tested was 3%. The average coefficient of determination, R^2, between the measured and simulated daily flows was 0.85. Goodness-of-fit measures of this type should be presented with results from all models to facilitate evaluation of performance.

Table 2 presents a comparison on the basis of resolution, minimum basin size, repeat period, and cost of the various remote sensing devices currently available for snow mapping. As indicated, digital snow mapping is more expensive than photointerpretation; however, it can be used on smaller basins and it is especially useful in areas of discontinuous snow cover such as Scandinavia.

Figure 2 is a comparison of SRM simulated versus measured flows for the South Fork of the Rio Grande basin in a high runoff year (1979) and a year of record low flow (1977) obtained in a cooperative project with the SCS (Shafer et al. 1982). SRM performance is good in both extreme years. In general, simulation results tend to degrade as the quality of input data decreases, which in most cases occurs as basin size increases. Techniques are currently being developed for using SRM in the forecast mode. To aid in application of SRM to a basin, a user manual including a sample data set is now available (Martinec et al. 1983).

MODEL MODIFICATIONS (TYPE 2)

Unfortunately, there are not many models that can use remote sensing directly such as those in the previous section. Most commonly used hydrologic models could also use remote sensing data, but only with modifications. In many cases, although the models have parameters that could be supplied by remote sensing, adaptations have been made to artificially generate the data or to use alternate parameters. As a result, either modifications of model structure or, at the least, new calibrations will have to be made in order to operate the models with remote sensing data. Several models have been identified as amenable to remote sensing after modification. They include the National Weather Service River Forecast System (NWSRFS) model (including the snowmelt portion); the Stanford Watershed Model IV; the Storage, Treatment, and Overflow Runoff Model (STORM); the Streamflow Synthesis and Reservoir Regulation (SSARR) model; and the Chemicals, Runoff, and Erosion from Agricultural Management System (CREAMS) model. Modifications have already begun on the NWSRFS model for eventual testing with remote sensing data (Peck et al. 1983).

In addition to modifications of the models, the remote sensing and conventional hydrologic data should be integrated to come up with the best estimate parameter for use by the model. Such a method has been developed by Johnson et al. (1982) and is called the Correlation Area Method (CAM). This method takes into account that there are certain basic differences in spatial and temporal coverage of various types of data. The CAM can apportion and weight conventional point data, aircraft flight line data, and spaceborne large-area-coverage observations over the same basin. Different combinations of data will be available at different times, and CAM will allow basin-wide parameter estimates based only on the data available at a given time. Thus, data missing from certain sensors at any time will not prevent operation of the model.

A NEW REMOTE SENSING COMPATIBLE MODEL (TYPE 3)

Probably a more effective, long range way of using the remote sensing data as input to hydrologic models is to develop new models that are designed to be completely compatible with this new technology. Such a model would be designed to use the general hydrologic land cover categories available from satellites; snow-covered area for driving a snowmelt runoff algorithm; surface soil moisture available from microwave data for soil moisture accounting and linkage to a soil moisture profile model; vegetative indices, biomass estimates, and surface temperature for evapotranspiration and interception calculations; and high resolution data for channel network and overland flow considerations. Such a model is currently being developed at the University of Maryland (Groves and Ragan 1983). In addition to making optimum use of the spatial and temporal characteristics of the remote sensing data, the new model employs a geographic information system (GIS) as an integral feature for overlaying data, merging data of different characteristics, and performing hypothetical basin treatments for design studies. The digital format of the remote sensing data and the large volume of data that can be collected with remote sensing make the use of the GIS approach very desirable.

Table 2.—Characteristics of various remote sensing data used for snow-cover mapping

Platform sensor/data	Nominal Resolution (visible)	Minimum basin size (digital/photo)	Repeat period	Cost in US $ (Tape/photo)
Aircraft				
- Orthophoto	3 m	1 km^2	as needed	variable
Landsat				
- TM	28.5 m	2.5/5 km^2	16d	2800/33
- RBV	40 m	5/10 km^2	18d	1300/30
- MSS	57 m	10/20 km^2	16d	650/30
NOAA				
- AVHRR	1.1 km	200/500 km^2	12 hr	99/8.5
GOES				
- VISSR	1.1 km	200/500 km^2	as needed	99/8.5

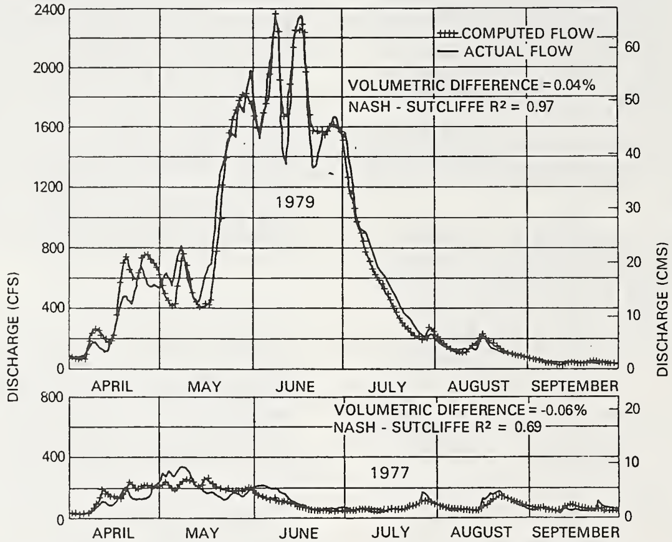

Figure 2.—Snowmelt runoff model simulated versus measured flows for the South Fork of the Rio Grande (Colorado) for a wet year (1979) and a dry year (1977).

CONCLUSIONS

Remote sensing is an important new data source for use in hydrologic and natural resource models that up until now has not been fully exploited. For example, the definite potential to obtain areal soil moisture information should be of value to most models operating now or being developed, whether they are oriented to water supply, crop yield, irrigation scheduling, or erosion estimation. From presentations at this symposium, I believe there are many opportunities to use the remote sensing information in the ARS natural resource models and major research investigations in this area should be initiated. An integral part of such a program would be the use of geographic information systems to manipulate remote sensing and other sources of data. The use of a correlation area method would permit merging of the various data types, and would also allow the models to be run, even if certain sources of data were not available at a given time. The successful use of remote sensing data should both improve model simulation accuracy and increase the situations in which a model is applied.

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ARS MODELING OVERVIEW - REMOTE SENSING - DISCUSSION

S. W. Robbins[1]

The author (Rango) discusses applications of satellite technology to hydrologic models. The Soil Conservation Service (SCS) has been using remotely sensed data in hydrologic models and for natural resource inventories for years. Aerial photos rather than satellite data have been used to determine land use, and soils maps have been used to determine hydrologic soil groups for use with SCS's Hydrology Computer Program for Project Formulation (TR-20).

SCS has cooperated with the Agricultural Research Service (ARS) in a study using LANDSAT data to estimate land use and cover conditions for use in SCS hydrologic models. We have had some success in the Northeast. It is more economical to use satellite data for larger drainage areas, such as river basins and large watersheds, than for smaller areas. Our need for satellite data for hydrologic models has decreased because very little watershed and river basin work has been going on for several years.

Because much of our work is in urban and urbanizing areas, where we are dealing with very small watersheds, many of the data now available are not being used. Improved sensors and resolution may allow mapping of varied land-use conditions at a small enough scale, which would greatly increase opportunities for use of satellite data.

A key aspect in hydrologic modeling is the soil moisture. Rango indicates that a number of current experiments are expected to increase our capabilities to measure moisture below the soil surface. Many hydrologic models need data on soil-moisture characteristics at depths of 2 to 3 feet. Can we, even in the future, penetrate to these depths with a good degree of reliability?

There is no question that with full use of existing technology and with future improvements in technology, remote sensing should both improve the accuracy of our model simulation and increase its potential use. The cost effectiveness of remote sensing may vary, depending upon the types of data needed, the resolution available, ground truth required, and the resources required to process the data.

To date in SCS, satellite-based methods have not replaced existing methods. We believe that in the future, remotely sensed data may be competitive with data obtained from other sources. We will continue to encourage and cooperate with efforts to this end.

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HYDROLOGIC CLASSIFICATION OF SOILS

D. L. Brakensiek and W. J. Rawls[1]

PROJECT DESCRIPTION

The subject of our report on the hydrologic classification of soils had its origin as a National Research Project established for research needs and was addressed in the Explanatory Notes for the FY 1979 ARS budget. The following excerpts from these notes address the need for change:

"Federal action and regulatory agencies in cooperation with State and local planning agencies have been directed by Congress through the Federal Water Polution Control Act of 1972, the Resource Conservation Act of 1977, and the Rural Clean Water Act of 1978, to develop programs to reduce nonpoint source pollution and to assess the impact of such programs on the quality of the Nation's surface and subsurface waters."

"One way to implement water quality programs is to monitor each watershed and prescribe corrective measures when pollution is judged to be excessive. A more feasible alternative is to develop accurate mathematical models to predict the effect of different management practices so that farmers and land use planning groups can select the Best Management Practices (BMP's) for each farm and watershed. Before this can be done, however, we need better ways to characterize the behavior of water intake, storage in soils, and runoff on a field and watershed basis. This research is essential to underpin the Department's ongoing and planned programs for protecting and improving water quality."

The nature of change, or impact of successful research on hydrologic classification of soils was visualized as follows:

"If successful, this research will provide a framework for using the extensive soil classification data base developed by the Soil Conservation Service (SCS) for evaluating management practices as they affect runoff, erosion, and chemical transport. In cooperation with SCS, this would improve the hydrologic classification of soils using soil morphologic and taxonomic data from standard soil surveys."

Specific objectives for research on the hydrologic classification of soils were to--"(1) evaluate the effects of cultural practices, flora and fauna, surface roughness, and water application methods on the hydraulic properties of soil; (2) develop a hydrologic classification of soils based on soil morphology and taxonomy; and (3) evaluate the effects of the point-to-point variability in soil properties on the movement of water, sediment, and agricultural chemicals."

During the past 3 years, we have concentrated on objectives 1 and 2. Emphasis has been on estimating procedures which utilize available soil data bases. The influence of cultural and agronomic practices on soil water properties has also been investigated.

The results of this project have also been used to relate the derived soil parameters to factors in the SCS curve number procedure. Our main accomplishment here is a procedure for classifying soils as A, B, C, or D.

GREEN-AMPT INFILTRATION PARAMETERS FOR HYDROLOGIC CLASSIFICATION OF SOILS

Many of the consequences and consistencies (or inconsistencies) of the SCS curve number runoff prediction procedure are well known. Central to the curve number procedure are SCS table 9.1 and figure 10.1 (Soil Conservation Service 1972). Much of the narrative of the "Hydrology Guide" pertaining to their runoff equation relies on soil and agronomic principles. This is not unexpected as its empirical base is observed rainfall-runoff events from agricultural plots or small watersheds.

Our studies on estimating soil water retention (Brooks and Corey equation) and infiltration parameters (Green and Ampt equation) from soil and agronomic factors have provided some useful predictive procedures and insights into the hydrologic soil grouping as embedded in SCS curve number hydrology.

Our hydrologic classification of soils also relates to a soil-cover complex, which is a combination of the hydrologic soil groups and land use and treatment classes.

HYDROLOGIC SOIL GROUPS

The hydrologic parameter on which the SCS based their hydrologic soil groups is a minimum infiltration rate, that is, "the minimum rate of infiltration obtained for a bare soil after prolonged wetting" (Soil Conservation Service 1972). The original soil listing was based on rainfall-runoff data from small watersheds or infiltrometer plots.

However, the majority of their present list is based on the judgments of soil scientists who use physical properties of soils and correlations with those soils already classified. They assumed that the soil surfaces were bare, that maximum swelling had taken place, and that rainfall rates exceeded surface intake rates. Thus, most of the classifications are based on the premise that similar soils (similar in depth, organic-matter content, structure, and degree of swelling when saturated) will respond in an essentially similar

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manner during a rainstorm having excessive intensities.

Four groups, A, B, C, and D, were defined by SCS soil scientists, with numerical limits established by Musgrave (1955). We have assumed that the conductivity parameter, K, of the Green and Ampt infiltration equation, which is approached after prolonged wetting, corresponds to the minimum infiltration rate used in the SCS classification of soils. The Green and Ampt equation is

$$f = K(1 + \frac{\psi_f n}{F}) \qquad (1)$$

where K = conductivity parameter,

ψ_f = wetting front suction parameter,

n = available soil porosity,

f = rate,

and F = accumulated amout.

K is one-half of the saturated conductivity, K_s.

Figure 1 is a soil texture triangle upon which the numerical limits for K have been used to delineate the hydrologic soil groups. This chart is adapted from our work on predicting Green and Ampt parameters from soil texture, organic matter content, and tillage practice factors (Rawls et al. 1983). The zero percent porosity change applies to the initial soil state.

An earlier report of our work presented the following tabulation of soil groups based on average soil texture conductivities:

Hydrologic soil grouping	Soil textures
A	Sand, loamy sand, and sandy loam
B	Silt loam and loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, and clay

This grouping was compared with soil groupings found in the SCS SOIL 5 File and is consistent with their A, B, C, and D classification.

Comparing the tabulation with figure 1 clearly shows the lumping involved in classifying soils only according to a soil texture class. For example using texture class, only, places a silt loam in a B group, whereas using particle size percentages (and organic matter) can place it in any of the four groups. The A and D soil groups are most nearly invariant with respect to soil texture. This lumping would infer inconsistencies in using curve number hydrology as part of a more physical based and distributed watershed model. However, the lumping of soil textures in soil groups is entirely consistent with the way that they were originally derived, that is, from small watershed or plot data.

Figure 1 can be used in curve number hydrology to group soils from available SCS soil survey information. Application of figure 1 to a soil profile containing several horizons of different texture can be handled by using the harmonic mean of the horizon conductivities. This requires definition of an effective or wetted soil depth.

GREEN-AMPT PARAMETERS

Figure 2 presents the Green and Ampt effective porosity parameter. The hydrologic soil groups do not line up with a particular effective porosity value. Figure 3 presents estimates of the Green and Ampt wetting front capillary potential parameter. There is a tendency for hydrologic soil groups to be characterized by a particular wetting front potential, that is, A = 10 cm; B = 20 cm; C = 40 cm; and D = 50 cm.

Even though figures 1, 2, and 3 indicate the SCS hydrologic soil groupings are not uniquely related to soil hydraulic and hydrologic properties, they do show that the Green and Ampt parameters can be estimated from readily available soil properties.

INITIAL ABSTRACTION

An advantage of the infiltration approach is that infiltration prior to runoff can be calculated (Mein and Larson 1971). The component of curve number hydrology, initial abstraction term I_a, is thus calculated rather than assumed to be a fixed percentage of total soil storage.

LAND USE AND TREATMENT

The cover component of the hydrologic soil-cover complex includes land use, land treatment, and land use and treatment class (hydrologic condition). The last appears to refer to the quality of the agronomic condition. We have developed a procedure to incorporate a change in soil porosity, which may result from agronomic practices, into estimating Green and Ampt infiltration parameters. From this result, it can be shown that the hydrologic soil grouping is not a fixed soil parameter but is significantly changed by soil porosity changes.

The physical condition of soil is significantly influenced by practices such as tillage, compaction, consolidation, crusting, incorporation of organic amendments, soil surface roughness, and vegetation cover. These can primarily influence the hydraulic properties of soils through changes in soil porosity. At present, our assumption is that the principal influence of agronomic practice is to change the total soil porosity. The pore-size distribution may also change, but there is little data on this aspect. Rawls et al. (1983), from a search of research data, were able to relate an initial increase in porosity to

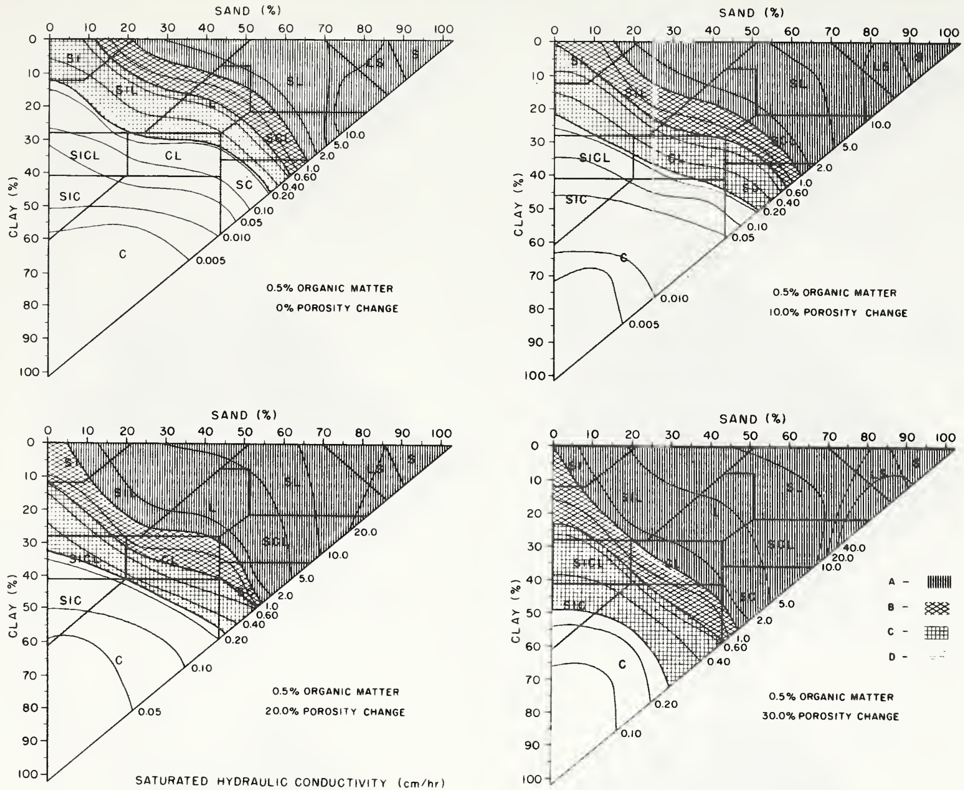

Figure 1.--SCS hydrologic soil groups.

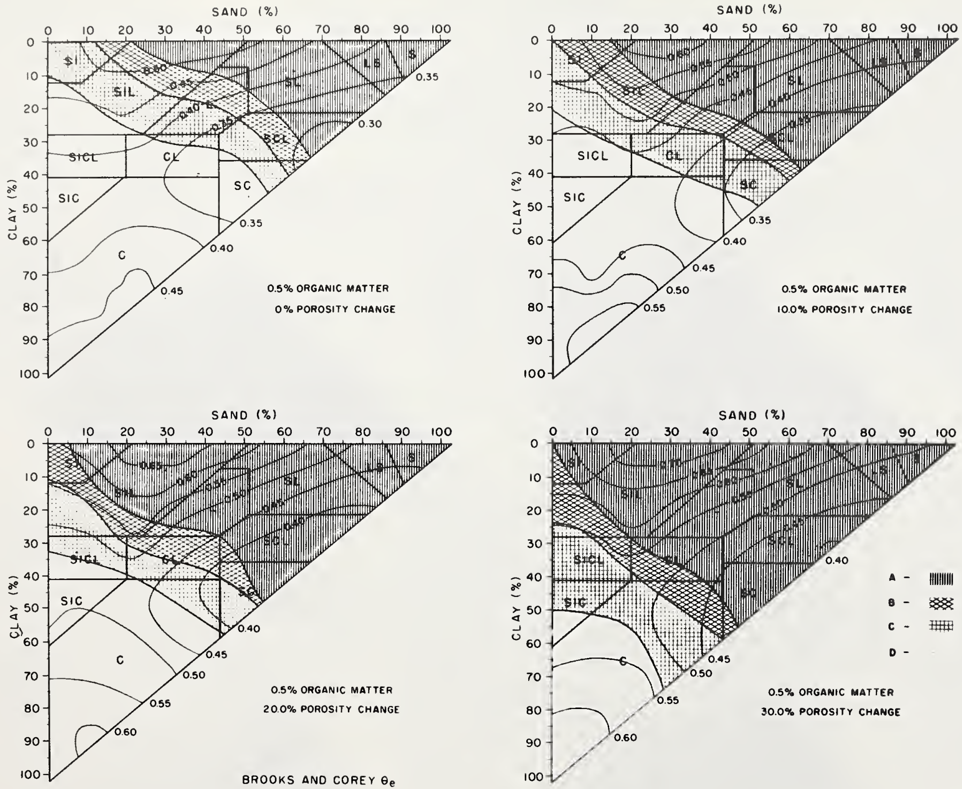

Figure 2.--Effective porosity for soil groups.

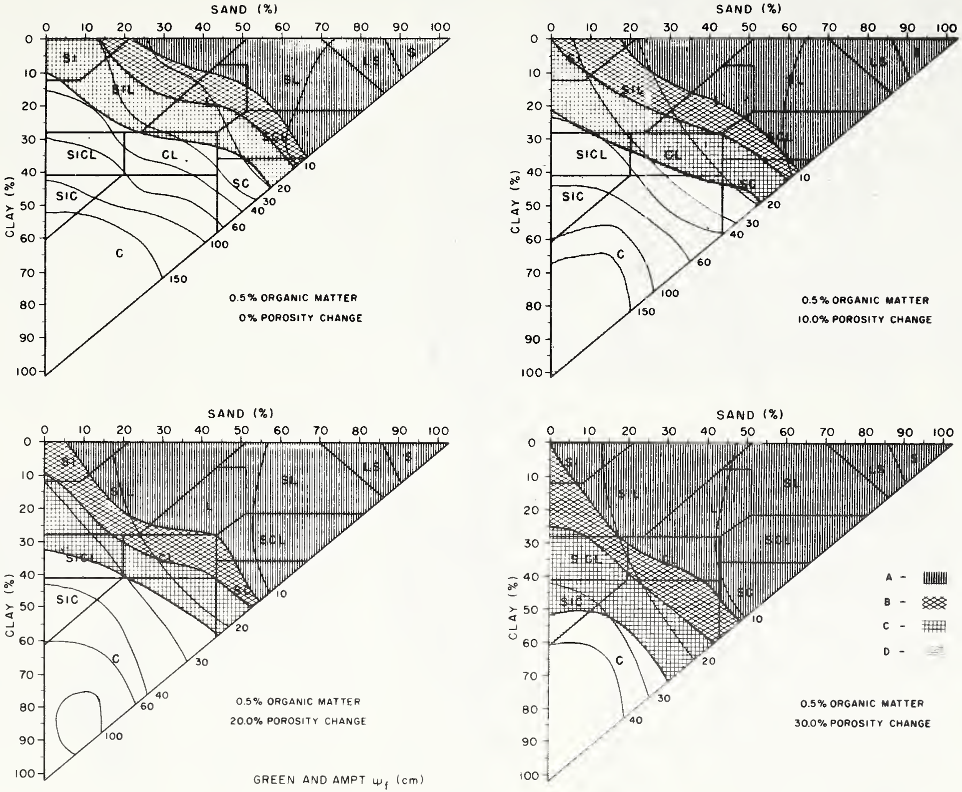

Figure 3.--Wetting front suction by soil groups.

various tillage practices. They also determined seasonal decreases in porosity on tilled soils because of natural processes causing consolidation. Rawls (1983) developed a procedure to predict an increase in soil bulk density (porosity is calculated from bulk density) due to changes in soil organic matter.

The additional charts in figures 1, 2, and 3 present the effect of an increased soil porosity, that is, 0 percent, 10 percent, 20 percent, and 30 percent, on the Green and Ampt parameters. Also delineated in these figures are the SCS hydrologic soil groupings. As an indication of the magnitudes of porosity change to be expected, we found that moldboard plow tillage on a sandy loam increased the total porosity by 30 percent. During the growing season (May to October), the sandy loam porosity decreased 10 percent due to natural processes such as consolidation. On a sandy loam (60 percent sand and 10 percent clay), a change of soil organic matter from 0.5 percent to 2 percent increased the porosity from 0.45 to 0.49, almost a 10 percent increase. Porosity changes due to other agronomic practices still need to be developed from published information. These charts, however, indicate that the hydrologic soil group cannot be considered as an inherent soil property.

CONCLUSIONS

An extensive analysis of soil water data has been used to develop predictions for Green and Ampt infiltration equation parameters. Inputs for these estimates are sand and clay percentage, organic matter percent, and a change of soil porosity (percentage). The set of predicted parameters can be used in an infiltration equation to estimate surface runoff.

The SCS hydrologic soil grouping has been defined by limits of soil conductivity. The groups were superimposed on the Green and Ampt charts. The K and ψ_f parameters appear to stratify according to the groups. However, the effective soil porosity, ϕ_e, which relates to the potential retention, S, does not relate to the grouping. In all cases significant lumping is present. It seems to the authors that this supports the use of curve number hydrology in lumped watershed modeling.

The authors submit that the Green and Ampt parameter charts should facilitate the use of an infiltration based runoff model. The impact of agronomic practices on infiltration is inputed by a change in soil porosity.

From the results reported here, a soil can be classified by its Green and Ampt parameters, K, ψ_f, ϕ_e. To accomplish this classification, readily available soil information--percent sand and clay and percent organic matter--and an estimated soil porosity change are required. Tillage effects and incorporation of organic matter can be accounted for by relating them to porosity changes. Progress has been made, but not reported here, on modeling soil crusting (Brakensiek et al. 1983). Other influences, such as soil compaction and soil fauna and flora, still require research.

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AGRICULTURAL MANAGEMENT EFFECTS ON SOIL WATER RETENTION

W. J. Rawls[1]

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INTRODUCTION

Average parameter values for the Brooks and Corey water retention model based on readily available soil properties have been published for agricultural soils (Rawls et al. 1982a). Modified procedures are needed to predict changes in the soil water properties caused by farming practices such as tillage. Tillage significantly alters the surface roughness and total porosity of the soil layers. The effects of various types of tillage on water holding properties of soil have been studied for specific soils. However, there is a need to quantify the general effects of tillage on soil water retention properties. It is the purpose of this paper to develop useful guidelines on predicting the effects of tillage on soil water retention as a function of readily available soil data.

It has been shown that the Brooks and Corey equation (Brooks and Corey 1964) provides a reasonable representation of the water retention matric potential relationship for tensions (negative pressures) less than 50 cm (Brakensiek et al. 1981). This equation is written as

$$S_e = (\psi_b/\psi)^\lambda \qquad [1]$$

where

S_e (effective saturation) $= \dfrac{\theta - \theta_r}{\theta_e}$

θ_e (effective porosity) $= \phi - \theta_r$

θ = soil water content, cm^3/cm^3

θ_r = residual soil water content, cm^3/cm^3

ϕ = total porosity, cm^3/cm^3

ψ_b = bubbling pressure, cm

ψ = capillary pressure, cm

λ = pore size distribution index

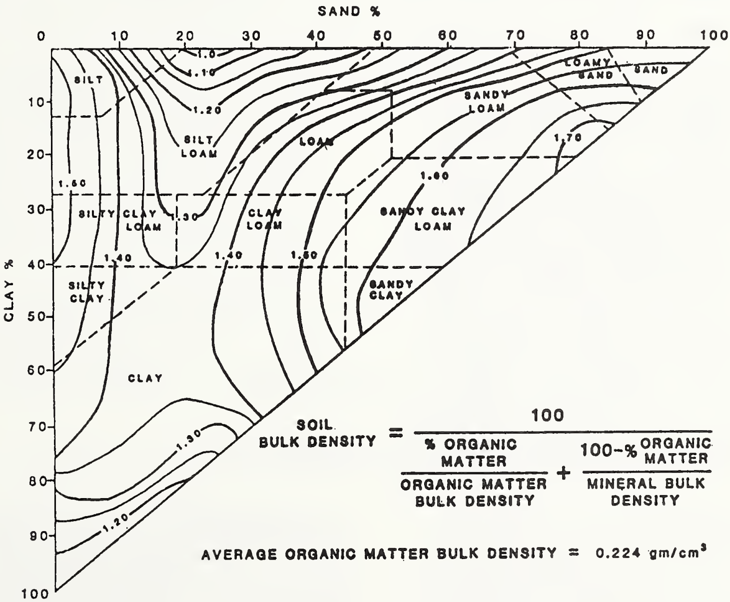

Figure 1.—Mineral bulk density.

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Table 1.--Coefficients for linear regression equations for prediction of volumetric soil water (sw) contents at specific matric potentials[1]

Matric potential bars	Intercept	Sand %	Clay %	Organic matter %	Bulk density g/cm^3	R^2
-0.20	0.4180	-0.0021	0.0035	0.0232	-0.0859	.75
-0.33	0.3486	-0.0018	0.0039	0.0228	-0.0738	.78
-0.60	0.2819	-0.0014	0.0042	0.0216	-0.0612	.78
-1.0	0.2352	-0.0012	0.0043	0.0202	-0.0517	.76
-2.0	0.1837	-0.0009	0.0044	0.0181	-0.0407	.74
-4.0	0.1426	-0.0007	0.0045	0.0160	-0.0315	.71
-7.0	0.1155	-0.0005	0.0045	0.0143	-0.0253	.69
-10.0	0.1005	-0.0004	0.0044	0.0133	-0.0218	.67
-15.0	0.0854	-0.0004	0.0044	0.0122	-0.0182	.66

[1]For -15 bars: SW = 0.0854 - 0.0004 (% Sand) + 0.0044 (% Clay) + 0.0122 (% Organic Matter) - 0.0182 (Bulk Density)

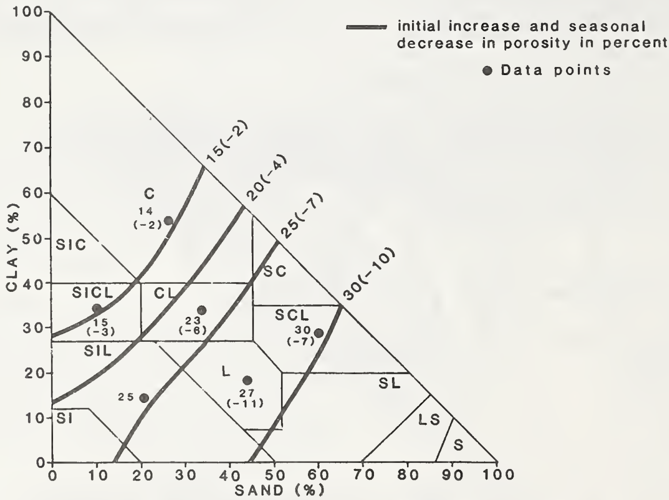

Figure 2.—Percent porosity increases due to a moldboard plow (percent decreases during the growing season) as a function of soil texture.

SOIL WATER RETENTION

The soils data needed to quantify the soils and management effects on water retention are particle size distribution (% sand and clay), % organic matter, and bulk density. Soil survey descriptions can be used to estimate the above soil properties if measured values are not available (Rawls et al. 1983). Also, figure 1 can be used with estimated or measured particle size distribution and organic matter to estimate bulk density (Rawls 1983).

Regression equations were used to predict the soil water held at nine tensions between 0.2 bar and 15 bar (table 1) with sand, clay, organic matter, and bulk density as input (Rawls et al. 1982a). These equations indicate that as bulk density decreases, the water retained at all tensions increases. The magnitude of increase is greater at the 0.33 bar than at the 15 bar. This could reflect a shift of the pore size distribution toward larger pore space.

The influences of tillage, additions of organic matter, and soil modification are represented as changes in total porosity (Brakensiek et al. 1982). Figure 2 shows the percent porosity change due to moldboard tillage according to soil texture. A porosity change for other tillage practices can be determined by multiplying the porosity change caused by plowing, given in figure 2, by the factor given in table 2 for the specific tillage practice. Values given in table 2 can also be used in conjunction with experience to determine porosity changes for new tillage methods.

Table 2.--Tillage induced porosity changes for different tillage systems

Tillage System	Ratio: $\frac{\text{Total porosity after tillage for given tillage}}{\text{Total porosity after tillage for plow}}$
Chisel	1.02
Plow-Disk-Harrow	0.97
Rotary	0.95
Plow and Pack	0.82

For 5% increments in sand and clay the equations in table 1 were used to simulate water retention values for the base porosity obtained in figure 1 and for 10% incremental changes ranging from 40 to 60% of the base porosity resulting in 640 sets of nine water retention values. The Brooks and Corey parameters (ϕ_e, θ_r, λ, ψ_b) were estimated by an optimized fit of equation [1] to each of the 640 sets of nine water retention values. Using nonlinear regression techniques the Brooks and Corey parameters were correlated to % sand, % clay, and porosity in the following equations:

$$\begin{aligned}\theta_r = {} & -0.0182482+0.00087269*SA+0.00513488*CL+ \\ & 0.02939286*POR-0.00015395*CL**2- \\ & 0.0010827*SA*POR- \\ & 0.00018233*(CL**2)*(POR**2)+ \\ & 0.00030703*(CL**2)*POR- \\ & 0.0023584*(POR**2)*CL\end{aligned} \qquad [2]$$

$$R^2 = .75$$

$$\phi_e = POR - \theta_r \qquad [3]$$

$$\begin{aligned}\psi_b = {} & EXP[5.3396738+0.1845038*CL- \\ & 2.48394546*POR-0.00213853*CL**2- \\ & 0.04356349*SA*POR-0.61745089*CL*POR+ \\ & 0.00143598*(SA**2)*(POR**2)- \\ & 0.00855375*(CL**2)*(POR**2)- \\ & 0.00001282*(SA**2)*CL+ \\ & 0.00895359*(CL**2)*POR- \\ & 0.00072472*(SA**2)POR+ \\ & 0.0000054*(CL**2)*SA+ \\ & 0.50028060*(POR**2)*CL]\end{aligned} \qquad [4]$$

$$R^2 = .88$$

$$\begin{aligned}\lambda = {} & EXP[-0.7842831+0.0177544*SA-1.062498*POR- \\ & 0.00005304*SA**2-0.00273493*CL**2+ \\ & 1.11134946*POR**2-0.03088295*SA*POR+ \\ & 0.00026587*(SA**2)*(POR**2)- \\ & 0.00610522*(CL**2)*(POR**2)- \\ & 0.00000235*(SA**2)*CL+ \\ & 0.00798746*(CL**2)*POR- \\ & 0.0067449*(POR**2)*CL]\end{aligned} \qquad [5]$$

$$R^2 = .98$$

where

SA = % sand
CL = % clay
POR = porosity (cm^3/cm^3)

Analysis of the predictions indicate that equations 2, 3, 4, and 5 are valid in the following texture ranges:

$5\% \le$ % sand $\le 70\%$
$5\% \le$ % clay $\le 60\%$

Using the above Brooks-Corey parameter equations in conjunction with equation [1] enables the prediction of water retention values for any given tension.

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ARS MODEL OVERVIEW - HYDROLOGIC CLASSIFICATION OF SOILS - DISCUSSION

Samuel W. Robbins[1]

The authors (Rawls and Brakensiek) have demonstrated that the SCS grouping of soils into hydrologic soil groups can be significantly improved if soil physical properties of hydraulic conductivity, porosity, organic-matter content, and percentages of sand and clay are evaluated.

Currently the SCS groups soils in hydrologic soil groups based on minimum infiltration rates. Soils with various combinations of texture are assigned a single hydrologic soil group. The lumping of soil textures in soil groups is consistent with the way that soil groups were originally derived from small-watershed or plot data.

The authors have shown that physical properties are not static and that, therefore, hydrologic soil classification cannot be static. Soil porosity, which has a significant effect on hydraulic conductivity, varies with tillage practice and season. Therefore, we need a classification based on infiltration in which the physical changes in soils can be evaluated. By relating infiltration parameters--wetting-front suction, hydraulic conductivity, effective porosity, and organic-matter content--to information on soil texture available from SCS soil surveys (Soils 5 table), a physically based infiltration model can be developed.

SCS is very interested in having a workable alternative to the curve number procedure. Such a procedure would be particularly useful for estimating the effects of conservation practices in reducing runoff from rainfall.

A significant amount of testing is required before a procedure useful to the field-level staff can be made available. We have been pleased with the close working relationships that we have had with the authors and we anticipate working together even more during the testing phase.

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SITE-SPECIFIC AUTOMATED DATA MANAGEMENT AND RETRIEVAL

C. R. Amerman[1]

Watershed and water resources field research involves the accumulation of large quantities of data. Many of the data are in such primary sets as those belonging to rain gauges and runoff monitoring stations, and are maintained in machine-readable form, usually compatible with mainframe computers.

Main data sets are often maintained as collections of individual files -- for example, a file of intensity-time data for a given rain gauge, maybe even a separate file for each year. These files may be held on several tapes, in boxes of punch cards, and so forth. Although more easily accessible than tabular data, such files are difficult to correct and update.

Other data sets contain land use and treatment histories or such auxiliary data as soil water content and temperature and soil parameter descriptions. Some contain relatively small amounts of data pertaining to specific research projects like the influence of macropores on water and nutrient movement, for example. These secondary data sets are often in handwritten form filed separately from the main data -- perhaps even scattered about among several researchers' files. Some such sets may be poorly maintained and may, for practical purposes, be lost if a scientist leaves. Retrieval of these data involves much more time and difficulty than when in machine-readable form.

Research analysis must usually be preceded by assembling data from several files. Even when all the files are accessible by mainframe computer, this can be a time-consuming process. Besides hindering productivity, an artifact of the difficulty of assembling data is the proliferation of duplicate (redundant) data sets. This complicates updating and correction procedures. Thus, there is potential for maintaining supposedly duplicate data sets whose contents differ.

The emergence of inexpensive desk-top microcomputers and mass storage devices has the potential, among others, for giving scientists almost immediate access to their data on demand. To realize the potential for efficiency and increased productivity that this hardware seems to offer, we must have well-designed software for the maintenance and manipulation of the data files, or, as their accumulation is commonly called, the data base. Scientists, however, should not have to concern themselves with the programming and maintenance of data filing and management systems.

A well-conceived hardware/software package for data base management should remove much of the frustration and a significant amount of the time involved in assembling data sets. It should provide the capability to store large amounts of data on-line and should provide ready and immediate access, with a few keystrokes, to any and all items in the data set in any combination.

The hardware/software package, alone, will not be enough. Research groups will also have to develop data management strategies as it becomes easier to manipulate data, disseminate them, and reproduce them. We will have to address questions relating to whom should have access to the data base for the purpose of making updates and corrections. We will have to devise schemes that assure that redundant data (in the same or separate data bases) are corrected at the same time as the main data base. We may wish to address questions of accessibility of a scientist's private data, that is, data which he or she has recently collected and has not yet exploited.

Numerous books that speak to data base management and to data base software are available on the shelves of many bookstores. From our standpoint as clients or users, the message seems to be that we should be able to expect data base software that is virtually transparent to most of us. We should be able to enter and extract data with little concern with how the base is internally organized. We should be able to quickly retrieve data from various parts of the data base and use those data in computational or graphics programs of our own design.

Several software vendors now offer data base management packages that will probably meet most, if not all, of our needs. These packages will run on hardware that uses the CP/M or MS-DOS operating systems, which are available or can be installed on nearly all microcomputers offered for office use. Varying amounts of memory are required by the several packages. Sixteen-bit microcomputers offer a greater range of memory options than eight-bit and sometimes run at higher speeds. Other operating systems are also available.

Freedom of choice in operating systems usually raises the issue of compatability between microcomputers. A communication mode called RS-232 and communications via telephone lines and modems alleviate much of this concern. At the North Appalachian Experimental Watershed, we freely pass data and programs between the products of three different vendors with three different operating systems, one of which is CP/M.

On-demand access to a data base at a location housing several scientists implies that each scientist be equipped with his or her own microcomputer, a concept that is feasible at today's

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prices for this type equipment. One can now buy a microcomputer work station with 25-line, 80-column display; two floppy disk drives; and a dot-matrix printer for a little over twice the cost, 15 years ago, of the rotary calculator that almost every scientist then had on his or her desk. After accounting for inflation, we can enormously increase a scientist's computational power at the same or lower cost than we spent on the rotaries.

With multiple work stations, thought naturally turns to interfacing them. There are several configurations available that offer different modes and degrees of intercommunication. The North Appalachian Experimental Watershed (NAEW), for example, did not feel the need for direct interfacing between scientists' microcomputers, but wanted each scientist to have direct access to the unit data bank contained on a hard disk system. A relatively inexpensive multiplexing system was selected for this purpose. The individual microcomputers contain their own intelligence and can be moved about, used independently of the others and of the data bank, and can be memory or otherwise configured independently of each other. The microcomputers may be configured with both 8- and 16-bit central processing units and may run under either CP/M or MS-DOS. The hard disk unit offers software switching that allows switching between operating systems when accessing a given file in either read or write mode.

Alternatives to the interfacing concept selected by NAEW ran between the extremes of none at all to systems in which all the intelligence is contained in a central processor and the desk units are only input/output devices.

Components were already on hand or were purchased to allow communication between the microcomputers at NAEW and other microcomputers or mainframes in either interactive or batch mode.

Those about to select microcomputer systems are often advised to select software and then to select hardware. For various reasons, this advice cannot always be followed. In any event, new software offerings continually appear, many of them adaptable to the commonly used operating systems. Alternative advice might be to select hardware with operating-system flexibility, thus, enhancing the prospect that future software advances may be utilized. Flexibility in the operating system is available in many moderately priced hardware offerings.

Hardware and software selection can be a time-consuming process, and there generally are no guarantees from any vendor that its product in combination with other system components will do the job the purchaser has in mind. About the only way to evaluate a product, especially in the software category, is to buy it and try it out. Magazines carry reviews of various products but do so mainly from a business viewpoint. Communications and Data Services Division of ARS provides valuable help in assessing needs and in selecting both hardware and software. However, experience with various products applied to research activities is rarely seen in print. The natural resources research groups should consider forming a loose-knit user's group that encourages an exchange of experience with both hardware and software applied in the research context. If the present business-oriented data base software is awkward or flawed when used in the scientific context, the natural resources groups should consider the pooling of funds to finance a research data management system.

We are entering a period in which a scientist can have individual access to enormous computing power right on his or her desk, where minutes, instead of hours or days, are needed for many data housekeeping tasks. Thoughtful selection of modern data processing equipment and of the data storage/retrieval facility should result in greater individual scientific productivity and, therefore, in greater unit and agency productivity.

DATA BASES FOR MODEL DEVELOPMENT AND TESTING: AN EXAMPLE

Donn G. DeCoursey[1]

The models described in the general session of this symposium are typical of future model development within the Agency. Research needs defined by the SCS and other agencies stress a complete systems approach to a variety of problems. Thus, models similar to those previously described will be needed. For example, improved descriptions of fish and wildlife habitat and habitat response to management and land use changes will require a model similar to SWAM, except that biological components will be needed for the stream system.

Models such as these require extensive data bases for development and validation. The chances of finding funds and support to provide new data bases are small. The alternatives are to add to an existing data base or use the results of a model that has been validated for describing missing parts of the system. Data collection and model development will be carried out only to the extent necessary to complete each study. The base model must have the desired accuracy and causal description of the physical system.

My purpose is to emphasize the fact that future modeling activity is likely to build on research and data bases already developed. However, many, if not most, of our data bases are not in a form suitable for model testing, especially the larger, more comprehensive models.

Validation of the SWAM model is to be made on as many data sets as we can develop. In our initial effort to assemble these, we elected to work with data from Four Mile Creek (University of Iowa), Rock Creek in Idaho (Saxton), Treynor Creek watersheds in Iowa, Watershed WE-38 near Klingerstown, PA, and Watershed W-3 from Sleepers River, VT. We felt that these data sets were as complete as we were likely to find and that they covered the range of components that need testing in SWAM. At the preent time we have only one data set completed, the Four Mile Creek watershed. Much of the credit for this is due to the Water Data Laboratory (WDL). Our staff in Fort Collins (Joann Ahrens, Mike Murphey, Carlos Alonso, and I) selected and assembled all the data to be included and developed a format to be used for compilation. Ralph Roberts of the WDL then developed the magnetic tape. We estimate that assembly took at least 1½ man-years. The data include watersheds 1, 2, 3, 4 and 8 and raingauges 33, 34, 35 and 36. We have 10 files on introductory watershed history, 10 files of climatological data, 8 files of runoff, 4 files of land management, 9 files of crop and crop cover, 4 files of soil water, 5 files of agricultural chemicals in soil and water samples, 6 files of herbicides in core samples, 7 files of nutrients in core samples, 6 files of herbicides in volume samples, 15 files of chemicals in runoff and sediment, 6 files of chemicals in draintile flow, 14 files on water and sediment yields and 3 files on soils—a total of 107 files. Mr. Burford will discuss efforts of the WDL in developing this set of data in the next presentation. Mr. Murphey has a display at the rear of the room to illustrate the problems in developing such a data set along with a handout describing the development.

We have assembled and developed about 70 percent of the Treynor Creek data and are working closely with Bill Gburek and Harry Pionke in assembly of the Klingerstown, PA, set. Our experience indicates that these sets (two to five sites in each) will require at least 1½ man-years. When we started assembling the sets, we had no idea that it would take so long; much of the data that must be assembled are in the form of handwritten notes in various office files. Only a limited amount of data, usually rainfall, runoff, and maybe some of the soil moisture, groundwater level records or sediment data are alread on tape. Data such as land use records; management (tillage, fertilizer, pesticide application, and so forth); crop yields and cover; chemical evaluation of soil, water, and sediment samples; some climatological data; soil moisture and sediment samples; and channel cross sections are seldom in a form that can be transferred directly to the final tape. The bulk of these data must be taken from field notes or data file sheets. This is very time-consuming. A big disadvantage in our assembly of data at Fort Collins is our lack of familiarity with the data for detecting errors and/or missing records.

In summary, I suggest that all research locations assemble <u>all</u> of their data in a tape file that can be made available to others involved in natural resources modeling efforts such as those being discussed at this symposium. At the present time much of our data are not being used, yet we can't afford new data collection. Thus, it is a necessity that we all take the time and make the effort necessary to compile our data into a usable form. The format that we developed for the Four Mile Creek data set could be used to guide discussions of a universal format (if one exists) to be used by all of us. I suggest that this be a high priority issue for the WDL advisory committee and that we seek administrative support to get the job done.

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PREPARATION OF FOUR MILE CREEK RESEARCH DATA INTO SMALL WATERSHED MODEL FORMAT

Ralph T. Roberts[1]

During the early stages in the development of the Small Watershed Model (SWAM), the Water Data Laboratory (WDL), USDA-ARS accepted the task of identifying, acquiring, and developing sources of existing research data which might be of value in testing and calibrating the various components of the SWAM. As a result of this responsibility, the laboratory became aware of the Four Mile Creek project, a 5-year cooperative research effort of the Iowa Agriculture and Home Economics Experiment Station, Iowa State University (ISU), and U.S. Environmental Protection Agency (EPA), Environmental Research Laboratory, Athens, GA. Data collected in support of this study were meant to provide an improved qualitative understanding of field-to-stream transport of sediment, nutrients, and pesticides and to provide a quantative basis for comparison against predictions from mathematical models on hydrology, erosion, and sediment and chemical transport.

During part one of the two-part study, which ran from 1976 through 1978, data were collected from the 50.5-km^2 watershed under existing watershed conditions. Part two of the study, running from 1979 through 1980, when EPA funding was terminated, involved ongoing collection of data concurrent with a concerted effort of promoting the use of best management practices system (BMPS) in the watershed through special educational efforts and increased cost sharing. The resulting 5-year period of record allowed researchers to evaluate the effect of BMPS on the water quality of agriculture drainage.

Since the Four Mile Creek project had as one of its research goals the collection of field data for use in validation of field-to-stream transport models, it was felt by all concerned that this project provided one of the most important data resources available for use in SWAM model validation.

Results of the Four Mile Creek project were made available to the WDL in a variety of media forms. General information on project objectives and methods, the study site, weather, fertilizer and pesticide application, crop inventory, and other related variables, as well as tabular listings of collected data observations were contained in a series of four annual reports, and two completion reports.

The annual reports (1975-76, 1976-77, 1977-78, 1979) by Howard P. Johnson, and the completion reports (1976-78, 1979-80) by Howard P. Johnson, J. L. Baker and C. N. Smith are available upon request from Iowa State University, 222 Agronomy Building, Ames, IA. Soils survey information and interpretation were provided in the form of an SCS preliminary report, "Advance Legend for Soil Survey of Tama County, Iowa Four Mile Creek Watershed," (available upon request) which inventoried the soil resources on the watershed.

The actual collected data observations were provided in three forms. The majority of the data were stored in digital form on a 9-track, magnetic tape containing 17 data files. Fourteen of these files contained valid data, the remainder were specified as unusable by ISU personnel. A portion of the data were provided in various tables and tabular listings within the above mentioned annual reports. Finally, a small segment of the data, the 1979-1980 soil core nutrient data, were provided to the laboratory in punched card form.

The multimedia form and voluminous nature of the materials provided by ISU prompted the SWAM team to take on the task of reformatting the information into a more manageable form before using it as a model verification tool.

As a first step in the reformatting effort, Michael R. Murphy and JoAnn Ahrens, hydrologic technicians with USDA-ARS, Fort Collins, CO, developed a skeleton format for a self-documenting magnetic tape for providing a single storage and transmission media for research data and associated textual and cartographic information. The result of their efforts was a magnetic tape containing summaries of the Four Mile Creek study's published textual information, a specification for data organization among the various tape files, and proposed data formats for the converted versions of Four Mile Creek data base.

This magnetic tape was transferred to the WDL, where I, as computer specialist, was assigned the task of merging the text and format developed by Murphy and Ahrens with the available data sources to form the final SWAM validation data base. This process involved the development of conversion software to process existing digital data into the new SWAM formats, use of interactive computer editing of observed discrepancies between existing digital data and corresponding published versions, conversion of tabular data from the study publications into digital form via word processors (only when a digital version did not exist), and conversion of stream cross-section plots to digital coordinate measurements using an in-house digitizer system.

The results of this cooperative effort is a 107-file magnetic tape which attempts to provide a complete, single-media, self-documenting, easily transmissible source of data for use in the

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validation and calibration of mathematical models being developed for use in the area of natural resources management. We hope that the end results of this development may serve as a guide in future data collection and storage efforts and that future decisions regarding data format, storage, and presentation will be made early in the process. We feel that the long term value and use of research project data can be most effectively and efficiently guaranteed if these kinds of decisions are made prior to, or during, data collection rather than after the fact, especially by persons not directly involved in the project, as has been the case in our work with the Four Mile Creek project.

DATA PRESERVATION

J. B. Burford[1/]

Successful computer model development related to natural resources usually depends on the availability of adequate historical data sets. Experience indicates that these required data sets are not readily available. The following comments relate to this situation.

The phenomena emphasized herein are not new; they have been recognized and discussed many times. Considerable progress has been made with regard to data preservation, but much more is needed, in my opinion.

Recent attempts by the Water Data Laboratory (WDL) to inventory ARS water related data combined with opportunities to assist in locating, obtaining, and organizing data sets, as related to the cooperative ARS modeling activities, have emphasized the following phenomena associated with data handling—

1. Many data sets have been obtained at field locations to support research dealing with plant-soil-water relationships and/or hydrology studies.

2. A high percentage of these data sets are not readily available in a usable form except, perhaps, for use by the researcher who obtained them.

3. Data sets, complete enough to sufficiently fill the needs for use with ARS modeling efforts such as the non-point-source pollution models are scarce.

Exact figures showing a breakdown of the research dollars as to the percentage used to obtain and process data versus other costs are not available, but it is apparent that the percentage is high, maybe 75 to 80 percent of the net project funds. Let us consider a hypothetical research project in hydrology, designed on the basis of 10 years of operation and involving one scientist and two technicians with salaries ranging from $35,000 to $45,000 and $13,000 to $20,000 per year, respectively, plus $10,000 per year for operating expenses. The total cost including salaries and operating expenses will be between $710,000 and $950,000 over the 10-year span. Based on the assumption that data collection and processing account for 75 to 80 percent of the total costs, the data set investments would range from $532,000 to $760,000. In addition to this large investment, there is the time cost of the 10-year waiting period.

Data obtained to support many of the soil-water-air and/or hydrology research projects have uses beyond those for which they were originally intended, thus providing side benefits or bonuses. Values of the side benefits are directly proportional to the degree of data documentation and to the degree which data have been organized, processed, and stored for reuse.

Considerable benefits would be gained if uniform data handling procedures were followed which would keep all data processed with a short lag time and in a universal uniform exchange format. No doubt there are existing procedures now in use which enhance data handling. Efforts are being made at some locations to concentrate on improving data management systems, reference C. R. Amerman's letter of July 13, 1983, "Data Base for Microcomputer in Research Application" and comments to be included in his presentation which follows this presentation.

During the fall of 1981, under the auspicies of the advisory committee, the WDL attempted to compile an index of soil-water-air related data sets residing within the many ARS projects. More than 90 projects were contacted by letter with a form to be completed and returned. Responses were received from 22 locations, 21 which identified existing data sets and 1 which had none. There is no explanation as to why the other 68 plus locations did not respond.

The 21 responses identified 132 data sets which have been grouped into 12 categories, including one miscellaneous group. Descriptive information indicates that 75 (57 percent) of the 132 data sets are computer accessible while 57 (43 percent) are either in tabular or analog form. If this fact can be used as an indicator, considerable work must be done to convert existing data sets to useable forms.

During the past 2 years the WDL has attempted to locate appropriate available data sets which could be used to develop and test the nonpoint-source pollution models. With the assistance of contacts in the Cooperative States Research Service, an appeal was made to the several State Experiment Stations for information about possible data sets. A notice was placed in Agricutural Engineering, January 1982, requesting information about appropriate available data sets. These efforts did result in a few leads, but follow-ups found a variety of situations. Generally, only partial data sets were available and a large percentage of these where not in computer compatible form.

A simple summary of the points made thus far indicate that: (a) large investments are made in obtaining data sets in connection with the various research activities, and (b) the full potential value of many of these data sets

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cannot be realized because they have not been well documented and converted to a computer useable form.

There are several possible reasons why the data sets have not been developed for maximum potential use. Some of them are—

1. Emphases have usually been placed on adhering to the policy of "publish or perish" with little or no recognition or credit given for data collection efforts.

2. Funds and staff are not available to fully support complete data processing and documentation.

3. Sufficient personnel are not available to spend time on what is deemed to be the lower priority work, such as processing data which are available but not needed to complete a specific study.

4. The feeling of exclusive ownership of the data by the collector.

A review of the reasons for the existing situation seems to suggest the following approaches be considered for improvement.

1. Project design and goals to include complete data processing and documention.

2. Existing technology, such as data loggers and microcomputers, be used to obtain and manipulate data.

3. Credit and recognition be given for data collecting, processing, and documenting, with more emphasis being placed on the potential reuse of the data.

4. Sufficient funds and personnel be made available to support the project.

Prediction: A large percentage of the data presently being obtained will have very limited use or will never be used unless policies and procedures are changed.

OVERVIEW OF RETRIEVAL PROCEDURES FOR HYDROLOGIC DATA FROM ARS EXPERIMENTAL WATERSHEDS IN THE UNITED STATES (REPHLEX)

Jane L. Thurman[1/]

Precipitation and runoff data are stored in the ARS Water Data Bank in sufficient detail to produce continuous hyetographs, hydrographs, and accumulation graphs for individual storms. Daily, monthly, and annual accumulations can be derived or extracted from the data. The Water Data Laboratory (WDL) uses the USDA Washington Computer Center (WCC) facilities to maintain the data bank. When requests are made for copies of data stored in the ARS Water Data Bank, WDL personnel search out and transfer the requested data to transportable media. If copies of the data are requested on magnetic tape, user tapes are sent to the WCC by the WDL. The data are copied and the user tapes are then returned to the WDL for mailing to the requestor. The cycle is normally completed within 4 to 5 days. If additional data are requested, the entire process must be repeated. Advantages of the procedure are that fund exchange arrangements are not required and all necessary computer expertise is provided by the WDL.

Increased computer-related capabilities in general but particularly within the USDA, the apparent increased interest in water management, and the expanding awareness of the existence of the ARS Water Data Bank have encouraged the WDL to decrease the time lag in responding to data requests. Accordingly, the WDL has developed RETrieval Procedures for HydroLogic data from ARS EXperimental watersheds (REPHLEX) so that users of ARS water data may gain access to the ARS Water Data Bank interactively. REPHLEX procedures have been designed to be self-prompting to promote usability with minimum training in computer techniques and the internal mechanics of the ARS Water Data Bank.

The ARS Water Data Bank

The ARS Water Data Bank contains precipitation and runoff data collected from about 305 individual study areas operated by 11 ARS watershed research centers. The watersheds range from less than 0.2 ha (0.5 acre) to over 536 km^2 (207 $miles^2$). Rain gauge networks have from 1 to more than 200 recording stations per watershed. Length of records for individual stations varies from 1 to 45 years.

The ARS Water Data Bank is organized by station year of data, which is used here to indicate a calendar year of either precipitation or runoff data from a specific recording station. Most of the data stored in the ARS Water Data Bank are in breakpoint form, that is, an instantaneous rate (for runoff) or accumulation (for precipitation) recorded with an associated time. Raw breakpoint data are processed to provide elemental hydrologic information, such as accumulations, intensities, and volumes. Identification, applicable information codes, and calculated accumulation values are added to create a processed record. The processed breakpoint data are stored in sequential files as one breakpoint record per logical computer record. Each station year of data is stored as a cataloged data set on magnetic tape. There are, as of September 1983, over 12,000 such data sets and 7,700 and 4,600 station years of precipitation and runoff data, respectively, stored in the ARS Water Data Bank. These files are referred to as storage and retrieval (S&R) files.

In addition to the breakpoint data stored in the ARS Water Data Bank, there are a limited number of stations where only daily accumulation values are available. These data, also, are stored on magnetic tape in sequential files. For these data each logical computer record represents one station year. Only two of the REPHLEX procedures (DPQRY and DQQRY) can retrieve this type of data.

Special precautions have been taken to maintain information integrity of the ARS Water Data Bank. Accidental user errors are eliminated by restricting accessibility. REPHLEX procedures are designed to be "read only." The primary principle of this system is to copy data from the ARS Water Data Bank to user files, which can be manipulated by the user. The S&R files are read only by previously tested procedures. The data bank files are kept in the WCC tape-storage facilities, where a controlled environment is maintained. In addition to the S&R files, which are accessible via REPHLEX procedures, the WDL maintains at least two more copies of the data on magnetic tape. The WDL has also developed techniques using 16-mm microfilm as a medium for archival copies of the data.

An index containing a pictorial representation of data stored in the ARS Water Data Bank is available upon request. The report is titled "Summary of the ARS Water Data Bank." It is also available through the REPHLEX procedure SPRDSHT.

Using REPHLEX Procedures

Access to REPHLEX procedures to retrieve data from the ARS Water Data Bank is available to anyone with access to the WCC computer system. The WCC maintains an IBM 370/3033/3042 Attached Processor system, with an IBM 370/4341 as an auxiliary system. All processors run under the MVS operating system with the JES2 job entry subsystem and time-share option (TSO). Access

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to the system may be through interactive time-share terminals in asynchronous mode at line speeds from 110 to 1200 bits per second (BPS) or through remote job entry (RJE) terminals in synchronous mode at line speeds of 2400 or 4800 BPS for dial-up lines. Most teletype-compatible and Remote 3270-compatible terminals can be used to gain access to the WCC system.
Data requesters are billed via reimbursable agreements with the WCC for the computer costs of running REPHLEX procedures. Information pertaining to the establishment of reimbursable agreements and specific information are available in "REtrieval Procedures for HydroLogic Data from ARS EXperimental Watersheds in the United States (REPHLEX)," ARM-NE-9. A free copy of this publication is available from

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REPHLEX procedures are self-prompting, with step-by-step instructions displayed on an interactive time-share terminal for the data requester. The data requester is prompted for specific information pertaining to billing, program options, identification of desired data, and output destination. Prompts have been designed for maximum flexibility of program options while minimizing online time and terminal output.

Several of the REPHLEX procedures generate batch jobs, which are released to the operating system for execution. REPHLEX procedures that generate batch jobs can request an RJE terminal with a printer for the printed output. For users without access to an RJE terminal, the printed output can be routed to a printer at WCC or held on a special queue to be retrieved at a later time via an interactive terminal.

Magnetic tape files generated by REPHLEX procedures are standard-label, 9-track, and 6250 bits per inch (BPI). Record lengths and block sizes vary for each procedure. Disk files are stored on resident 3380 disk files.

Overview of Individual REPHLEX Procedures

WDLCOPY is the basic REPHLEX procedure used to retrieve data from the ARS Water Data Bank. This procedure copies one of more station years of breakpoint data to one of three destinations--magnetic tape files, online disk files, or printed listings. Either precipitation or runoff data may be retrieved but not simultaneously. Multiple years of data for multiple stations and multiple locations may be copied onto one output file. The output files are in the WDL standard format. Copying data using the WDLCOPY procedure at normal priority costs $3 plus approximately $0.35 per station year of data.

IDENT provides the data requester with basic information about a watershed such as location, original identification, acreage, latitude, and longitude. This procedure has no output other than the information returned to the user's terminal. Several generic searches may be made using this procedure to query for specific watershed characteristics. The "individual watershed" search will display all available information concerning a specific watershed. The "location" search will display all watersheds for a specific location number. The "watershed area" search can be used to check on the availability of data from watersheds within a specified area range. The "state" search will display all watersheds for a specific State. The "latitude-longitude" search prompts for coordinates to select watersheds within a rectangular area. Running the IDENT procedure costs approximately $0.85 per session, which is a function of online TSO time rather than program execution expense.

DPQRY provides daily totals for precipitation data stored in the ARS Water Data Bank. DQQRY provides either mean daily discharge rates or runoff volumes. Multiple stations for multiple years of data can be requested. Output from either procedure can be printed or copied onto magnetic tape. Printed tables provide monthly and annual precipitation amounts and discharge volumes, respectively, as well as daily totals. Using DPQRY or DQQRY procedures at normal priority costs approximately $5.10 per run.

PLOTYR is an interactive graphics program, which plots rainfall hyetographs superimposed over runoff hydrographs for intervals of up to 1 month. This routine is useful in selecting storm events from 1 or more station years of data. Selected parts of the same timespan can be plotted multiple times. Maximum peak flows are provided at the beginning of each month of data. Rainfall and runoff data must be available in online disk files in the WDL standard format (can be built using the WDLCOPY procedure). Plots may be generated either on a graphics screen or on a flatbed plotter using various types of equipment. Running PLOTYR costs approximately $0.50 per plot frame. About 30 seconds is required to create a screen plot and 1.5 minutes to create a pen plot at 1200 BPS. With no prior knowledge of the data selecting a storm event from a station year of data will typically require 30 plot frames, for a total expense of about $15.

SASPLOTP produces printer plots for rainfall hyetographs or accumulation curves. SASPLOTQ produces printer plots for runoff hydrographs. Specific timespans may be specified by the data requester. Multiple plots may be requested for each station year of data. Producing a printer plot using SASPLOTP or SASPLOTQ costs approximately $1.05 per plot at normal priority.

SASGRAFP is an interactive graphics program which plots rainfall hyetographs or accumulation

curves for selected time periods. SASGRAFQ is an interactive graphics program which plots runoff hydrographs for timespans specified by the data requester. Multiple plots may be generated during one session. Data for either of these procedures must be available in an online disk file in the WDL standard format (can be built using the WDLCOPY procedure). Plots may be generated either on a graphics screen or on a flatbed plotter using various types of equipment. Running SASGRAFP or SASGRAFQ costs approximately $3 per plot frame. About 30 seconds is required to produce a screen plot and 1.5 minutes to produce a pen plot at 1200 BPS.

SPRDSHT provides updated versions of a report titled "Summary of the ARS Water Data Bank." This report provides a pictorial representation of data stored in the ARS Water Data Bank. Station identification codes are displayed as they are used in the data bank files. Beginning and ending years of record as well as missing years are shown. The data requester may specify one or more locations to be printed. A complete summary listing at normal priority costs about $2.60. The minimum for listing one location is approximately $1.30.

NEWS provides a user of REPHLEX procedures with information pertaining to changes and additions to the system. The cost of running NEWS is nominal.

Conclusion

Hydrologic research programs have been of primary concern in the U.S. Department of Agriculture for many years. Precipitation and runoff records from various locations have been converted to computer-compatible media, copied, and sent to the Water Data Laboratory, where they have been stored in the ARS Water Data Bank. Approximately 7,700 years of runoff data and 4,600 years of precipitation data are currently available in a standardized format. Copies of the data can be made available through requests to the WDL. In addition to this process the WDL has developed REPHLEX procedures so that researchers can gain access directly to the ARS Water Data Bank via interactive terminals. Various procedures have been developed to provide copies of hydrologic data in breakpoint form, daily values tables, graphic and summary forms. Output options include printed material, magnetic tape, disk files and interactive plot images. Most teletype-compatible and 3270-compatible terminals can be used to gain access to the ARS Water Data Bank through REPHLEX procedures.

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ORGANIZATION OF NATIONAL DATA BASES FOR USE IN PROCESS MODELS

P. T. Dyke, W. Fuchs, and G. Wistrand*

As more and more process models move from the developmental stage to the operational stage, the need for a more thorough understanding of data requirements surfaces. Models developed to provide information needed for national policy decisions commonly involve an enormous number of variables and complex calculations. Because of this fact, every effort must be made to minimize the amount of data used in a model for large geographic areas and diverse management environments.

This paper describes the data bases that USDA assembled for the Erosion-Productivity Impact Calculator (EPIC), and the factors considered in designing these data bases. USDA learned a great deal about the relationships between models and data through this experience. Many of the lessons and much of the data apply to process models in a broad range of uses.

First, those of us on the data base design team assessed our situation by asking the following questions: From where are we starting? What must be produced to achieve our objectives? When must the task be completed? What resources are available to help us accomplish our task?

From where were we starting? Congress had handed USDA an assignment in the form of the 1977 Resource Conservation Act (RCA) to determine the effects of present resource conservation policy on the ability of following generations to produce food and fiber. One of the secondary relationships recognized as important for this policy analysis was the one between soil erosion and soil productivity. The 1980 RCA assessment had included a statistical model analysis known as the yield/soil loss simulator, which was an attempt to determine this relationship (Hagen 1980). But as that analysis was being completed, the results raised many questions for which satisfactory answers were not available.

What must be produced? We needed more definitive answers on availability of natural resources and soil degradation. Therefore, we needed to improve our data base and be able to integrate the physical processes involved in crop production and soil erosion.

When must the task be completed? We needed the operational model and data base in time to answer questions on erosion and productivity for the 1985 RCA report.

What supportive resources were available to help us accomplish our task? Those of us in USDA assigned to this task had libraries with information about plant and soil relationships. We had limited but valuable experience using comprehensive systems to integrate vast quantities of knowledge and data, very limited resources for collecting new data, large but finite quantities of computer power, limited human power, a lot of moral support from our administrators, and almost no time.

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ORGANIZING USDA RESOURCES

Our plan of attack called for researchers from the Agricultural Research Service (ARS) to link as many of the known relevant individual processes as time permitted into a comprehensive model (EPIC). The Soil Conservation Service (SCS) would provide any available soils data and land inventory data in national files. In addition, SCS would assist in compiling other basic data that could be obtained from its national technical centers and state offices. The Economics Research Service (ERS) would compile and organize the data, design and build the programs to store and retrieve the data, devise ways of estimating missing data, and in general be responsible for making data bases sufficiently complete to drive the EPIC model for all geographic areas of the United States. In addition, ERS would structure the output so it could be used by the National Linear Programming model to place dollar values on the impact of erosion on productivity.

The data bases had to meet the following criteria:

1. The composite data must provide consistent coverage of all of the United States except Alaska and Hawaii.

2. All data sets must be complete in order to make the model operative.

3. If empirical and/or secondary data were not available, estimates must be made and entered.

4. Data must be documented as to source and procedure for making estimates.

5. Data bases must be linked to the model programs to--a) minimize the errors introduced at run time and b) allow many runs of the simulation model within a short period.

6. The input and output data bases should be designed to accommodate 10,000 to 30,000 individual simulations (model runs) with the ability to statistically analyze both output and input data as independent variables when necessary.

7. The completed data base which drives the model should be compiled and stored so that model runs can be made on subsets of any or all of the physiographic, soil, and conservation management groups structured in the data base.

DATA STRUCTURE

We structured the data base around 168 physiographic producing regions identified as the Major Land Resource Areas (MLRA's) identified by SCS. For each area, the data base contains 10 to 25 crop rotations; a maximum of 8 soil types; tillage operations for 4 practices--fall plow, spring plow, conservation tillage, and zero tillage; 4 conservation practices--straight row, contouring, contour stripcropping, and terracing; irrigation and dryland designations; and one set of weather parameters.

The paragraphs that follow describe briefly the data assembled for driving the EPIC (RCA) model.

Weather Data

Weather data for a point near the center of each MLRA were assembled to reflect weather conditions for the entire MLRA. Weather and climatic data stored in this data base were needed as input into the weather generator subprogram of EPIC. Because historical daily data were not included, storage requirements for the data base were greatly reduced. Information stored included monthly values for maximum and minimum daily air temperatures; average precipitation, 30-minute rainfall intensity; wind velocity and direction; and probability parameters for rain, temperature, and solar radiation.

Soil Data

In order to assure ourselves that we were using the best and most complete soils data available, all of the SCS Pedon data (both computer and hard copy files) which could be collected in the time frame were pulled together with the assistance and cooperation of the National Soil Survey Laboratory (NSSL) in Lincoln, NE. Although some data processed by university and state laboratories in cooperation with SCS are included in the data base, state pedon data, by and large, remain an untapped resource.

From the approximately 12,000 soil series which have been named in the United States, SCS chose one to represent each of 8 RCA soil groups in each of the 168 MLRA's. For each of these series, SCS chose one representative pedon from the pedon data base. Thus, a subset of 880 pedons was chosen to represent the soils of the United States for the EPIC analysis. The larger data base of 11,500 pedons is, or course, available for additional analysis with EPIC and other process-type models.

Some of the information needed by EPIC is not included with the pedon data, so we had to extract parts of the soils interpretations data base maintained at Iowa State University (ISU) for the National Cooperative Soil Survey program. Information obtained from this data set include the taxonomic name, surface texture, surface organic carbon (used to calculate albedo), wind erodibility index, erosion K factor, erosion tolerance factor (T), estimate of profile depth, and hydrologic group.

Before the EPIC model will run, all soil data cells must be filled. Supplemental programs outside EPIC, regression equations, default values, value judgments by knowledgeable SCS soil scientists, and numerous other methods are used to estimate missing data. This RCA soils file and the slope file described below are the only soils files accessed by EPIC at run time.

Soil Slope Gradient and Slope Length File

Soil slope gradient and slope length are in a separate subset of the data base. Thus, specification by slope and slope length is possible for each soil group. Representative slope and slope length were assigned by SCS for each of the 8 RCA soil groups in each of the 168 MLRA's. Slope gradient and slope lengths from the 1982 Natural Resource Inventory (NRI) may be substituted for these values if the NRI becomes available within the time frame of this project. This gives reasonable flexibility for rapid analysis of various combinations of slope and soils.

Management and Operations Data Bases

These data bases take the form of (1) a crop rotation and tillage practice file, (2) machinery list file, (3) budget-cost file, (4) operations file, and (5) planting and harvest data file. Proper design and data filling of management files is extremely important when using process models for national policy analysis (or for any other use constituting large numbers of runs). For small geographic regions and special study areas, this type of information is generally (and rightfully) hand-fed at run time. For large numbers of geographic regions, improper handling of this part of the data processing will cause innumerable problems, major errors, and costly reruns. There are numerous ways to design, store, and access this management information. The files described here seemed to be our best compromise when considering ease of access, computer storage cost, run time flexibility, and run time hand entry inputs.

Crop Rotation and Tillage Practice File

Acceptable crop rotations are stored for each MLRA. These rotations are subdivided into as many as 4 tillage practices: fall plow, spring plow, conservation tillage, and minimum or zero tillage. Each crop in the rotation is numbered and indexed in a budget index file tillage schedule.

Crop Budget File

ERS conducts annually some phase of its cost of production survey. This survey collects not only cost data from farmers, but also information on time and types of tillage operations for major crops grown in a geographic region. This information is then compiled to provide cost and return information on the crops. The Firm Enterprise Data System (FEDS) data base provided a starting point for SCS, Iowa State University, and ERS to develop modified budgets that reflect the individual machinery operations in four

levels of tillage. When this is completed in early 1984, the files will be used to (1) create a budget specific to each tillage practice and (2) provide information for the operations file to EPIC.

Machinery Complement File

A machinery file is used by both the budget file of FEDS and the machine operations file of EPIC. The FEDS budget file includes data for each tillage implement. This list of 100 power units and implements includes such specifications of size, price, repair cost, power requirements, and so forth. The EPIC machine file includes for each tillage implement data on row width and random roughness coefficient (for wind erosion), plowing depth or cutting height, mixing efficiency, and an EPIC created category of seasonal operational use. These two machinery files have been given common codes to allow cross reference. All field operations are selected from this list of available and allowable machinery.

Machine Operation File

The machine operations file for EPIC is created by removing all non-tillage activities such as marketing from the budget file and assigning the day of year to each operation. FEDS records the month but not the day. EPIC daily operations are stored in reference to days before or after planting or harvest. The days assigned to this file are recorded in the rotation with all crop rotations using that sequence of tillage events.

Planting and Harvest Dates File

USDA's Statistical Reporting Service (SRS) has estimated planting and harvest dates for each crop in the 168 MLRAs. Modifications in planting dates due to double cropping, fallowing, previous crop, and so forth, can be made in the operations file by special coding.

Observations

Some data bases used to support process models may of necessity be model specific. However, the support data bases containing the basic data frequently are common to many models. Our experience has shown that most of the data base effort in the RCA activity was made in obtaining and organizing the basic data, not making it compatible with the specific model. Large national data bases which are being compiled for the RCA activity should be of considerable value to others interested in using process models.

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REPORT AND PARAMETER FILE GENERATORS

A. D. Nicks[1] and J. B. Burt[2]

INTRODUCTION

Most hydrologic transport models existing today require inputs that must be gathered from dispersed sources by the user. Depending on the complexity of these models, the task of working up required parameters is often time consuming and limits the usefulness of the model. Moreover, these models are capable of outputing a large volume of numbers, which often must be interpreted beyond the summary tables provided by the developer. Thus, methods to reduce time and labor involved in preparing inputs and interpreting and publishing reports of model results are imperative to better useability and acceptance of hydrologic transport models.

The availability of microcomputers and appropriate software greatly enhances model use by providing the user with inexpensive methods for analyzing and interpreting model results and by addressing the questions and answering the needs of the user. Presented in the following discussion are examples of using microprocessors and word processors in conjunction with model inputs and output report generation.

INTERACTIVE PROGRAMS

Microcomputer programs have been developed to construct parameter files for hydrologic transport models such as CREAMS(1) and SWRRB (Williams et al., this volume). The programs can be run on inexpensive microcomputers such as IBM, Radio Shack, Apple II, and so forth, which have FORTRAN and floppy disk operation systems (DOS) or CP/M systems. The programs are written to interact with the user to allow entry of specific parameter values or default tables on soil characteristics, climate data, crop growth indices, chemical characteristics data and application dates and rates. These programs provide the user with an easy method for constructing parameter files, often reducing their construction time from over 1 hour to less than 10 minutes. Similarly, programs to generate reports and summarize output files for the CREAMS model have been developed for microcomputers. Output files developed on large mainframe computers can be transferred to the microcomputers for further manipulation. These programs are particularly useful because their output can be transferred to word processors for publication quality printouts.

APPLICATIONS

Examples of input parameter generator outputs and report generation are shown in figures 1 and 2. Figure 1 is a listing made from a microcomputer for generation of CREAMS hydrology option 1 parameters for a watershed in Mississippi. Figure 2 is a summary sheet from a report generator for one management option in a study of the Mississippi Delta major land resource area (MLRA). These examples demonstrate the use of mainframe, minicomputer, microcomputer and word processing equipment with the aid of data communications software. Listed in figure 1 is a printed summary of the parameter values selected by the interactive parameter generating program for CREAMS hydrology option 1 (2). The printed summary file (shown) and a parameter input file in the model format (not shown) are constructed by the program. The printed output is useful in documenting the parameter values used in a particular model run, especially when several model runs are made with varying resource management systems. This type of report generation is also useful in achieving the various parameter sets for further application or review of options that may have been used in a particular MLRA.

Operation of the program consists of the user interacting with or replying to questions displayed on a terminal video screen. Tabular values of soil characteristics for major soil textural classes ranging from very fine sand (VFS) to clay (C) are available to the program for tablular look-up default values. Similarly, leaf area indices for 10 crops, and infiltration parameters for hydrologic soil groups are also available. The user, for example, may select from tabular values by replying "SiL" to the "Soil type?" query. As a result of this reply the typical default values for a Silt Loam soil are selected and put into the parameter file. The user may choose to hand enter individual values for the soil parameter, in which case the computer will lead through a series of queries that will construct specific soil, crop, or watershed configuration. Correspondingly, the user may enter the required climate inputs of 12 monthly values of mean air temperature and solar radiation. Typically, the parameter file generation can be completed in less than 10 minutes.

Figure 2 shows an example of machine processing of model output files from CREAMS hydrology and erosion model components runs in the Mississippi Delta MLRA. In this report generator example, provisions are made to summarize the daily outputs from the models' passfiles. Frequency analysis and statistical techniques were employed in the program to show the user, the expected average, driest year, and wettest year in ten years for a given set of field conditions such as soil, conservation practice, tillage system, and crop options.

Information listed in tabular form represents the values which would be exceeded 90, 50, and 10 percent of the time. Values for monthly precipitation, runoff, sediment yield, curve number, plant water uptake, and average profile soil moisture content are computed from normal and log-normal distribution techniques

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applicable to the best fit of the individual parameters. Twenty-year climatic data inputs were used in the example shown.

The purpose of this particular application is to generate tabular and graphical information for seven different resource management systems on three field locations typical of fields found in the Mississippi Delta MRLA. Information developed in this way, not readily available from the orginal model outputs, is then compiled into a field guide or manual that is in turn used to assist the planner and land owner in selecting the most appropriate system for installation to reduce sediment load delivery and to improve water quality.

The three-dimensional representation of the field topography, shown in the upper right hand corner of figure 2, is an additional feature added to the report generator output to illustrate more clearly the topographic roughness and setting of the field site. Fields of this type can be readily contrasted with other fields with different systems applied. For example, a field with land leveling practices applied and having the same cropping system and soil could be compared with the field shown. Thus, use of the report generator allows a more available comparison and representation of multiple model runs for different fields or mangements alternatives on the same field than is normally available in the original model outputs.

SUMMARY AND CONCLUSIONS

Parameter file and output file report generating programs are important techniques for saving time and reducing work load requirements in the application of operational water resource models. Front-end processing of parameter and climatic data inputs by inexpensive microcomputers is a technique that can be allied with hydrologic model development to enhance model use. Similarly, rear-end processing of basic computational outputs from such models can assist in achieving usage not envisioned by model developers, such as is needed in planning, evaluation, and development of improved resource management systems.

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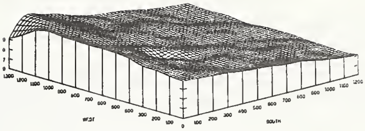
Title:
        MISSISSIPPI DELTA FIELD F NEAR BELZONI, HUMPHREYS CO. MS
     CONVENTIONAL TILLAGE CONTINUOUS COTTON ON ALLEGATOR AND FORESTDALE CLAY
       FIELD AREA = 35.60 ACRES SLOPE = .2%
     Drainage Area  35.600 Acres
     Average Watershed Slope   0.002
     Watershed Length-Width Ratio   4.000
     Condition II Curve Number  89.000
     Extraction Coeff.   0.200
     Saturated Hydraulic Conductivity   0.010 in/hr
     Soil Evaporation Coeff.   3.500
                Soil Properties
     Total Porosity   0.480
     Field Capacity   0.442
     Wilt Point   0.300
     Initial Moisture Contenet   0.500
     Plant Root Depth  40.000 inches
     Upper Limit of Soil Moisture Storage
       Depth  Storage
       (In.)  (In./In.)
         1.11   0.110
         6.67   0.550
        13.33   0.660
        20.00   0.660
        26.67   0.660
        33.33   0.660
        40.00   0.660
     Normal Monthly Temperature Deg.(F)
MONTH      1      2      3      4      5      6      7      8      9     10     11     12
        47.0   49.5   56.6   64.8   72.7   80.4   82.5   82.2   76.2   65.6   53.5   47.4
     Normal Monthly Solar Radiation (Langleys)
MONTH      1      2      3      4      5      6      7      8      9     10     11     12
       232.0  292.0  384.0  446.0  558.0  557.0  578.0  528.0  414.0  354.0  254.0  205.0
     LEAF AREA INDEX
           DAY   AREA
             1   0.000
           111   0.000
           128   0.130
           145   0.280
           162   1.050
           179   2.140
           196   2.960
           213   3.000
           230   2.960
           247   2.920
           264   1.780
           281   1.000
           282   0.000
           366   0.000
```

Figure 1. Example of print output from a CREAMS Hydrology option 1 model parameter generation microcomputer program.

FIELD SUMMARY
CREAMS MODEL

Field: F near Belzoni Humphreys Co., MS.
Area: 35.60
Max. Hydrologic Slope Level: 0.2%
Soil Type: Allegator and Forestdale Clay
Crop: Continuous Cotton
Management System: Reduced Tillage
Erosion Control Practice: Conservation Tillage
Chemical Management:
 Herbicides: Treflan, Cotoran, MSMA, Dinitro
 Insecticides: Bidrin, Pydrin,
 Bolstar, Orthene,
 Methyl Parathion, EPN, Pounce
 Other: DEF

FIELD F



AVERAGE FIELD VALUES

MONTH

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	
PRECIP	3.96	4.47	5.16	4.76	3.71	2.55	3.44	2.31	2.08	2.00	3.24	5.18	48.71	(in)
RUNOFF	1.21	1.89	2.18	1.91	1.28	.03	.23	.01	.02	.01	.32	2.22	17.54	(in)
CN	95.54	95.60	93.85	94.34	93.05	88.14	84.95	84.00	85.10	86.62	91.28	94.68	91.87	
MOIST	.47	.47	.47	.47	.47	.44	.40	.40	.40	.41	.43	.45	.44	
PL UP	.00	.00	.00	.03	.64	3.86	4.24	3.08	2.05	.55	.20	.00	12.45	(in)
PERCOL	.35	.40	.49	.53	.34	.17	.00	.00	.00	.00	.00	.00	1.39	(in)
SED YLD	.22	.33	.59	1.00	.68	.02	.11	.00	.00	.00	.09	.49	6.49	(T/Ac)

WETTEST YEAR IN 10

MONTH

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	
PRECIP	8.61	8.20	8.16	8.70	7.50	6.07	7.97	5.80	7.89	7.59	8.20	9.84	62.78	(in)
RUNOFF	5.96	5.47	4.82	5.38	3.65	3.84	7.37	1.09	3.22	1.75	7.82	10.35	27.38	(in)
CN	98.53	97.44	95.80	96.36	95.72	92.04	88.08	86.82	88.05	90.87	94.84	97.13	92.76	
MOIST	.48	.48	.48	.48	.48	.45	.40	.40	.41	.42	.44	.47	.45	
PL UP	.00	.00	.00	.04	.76	4.50	5.60	4.05	2.75	.80	.28	.00	15.12	(in)
PERCOL	.48	.50	.62	.66	.47	.25	.00	.00	.00	.00	.00	.00	1.78	(in)
SED YLD	1.29	1.26	1.14	3.37	3.00	1.86	3.41	.34	.78	.45	1.83	2.32	9.86	(T/Ac)

DRIEST YEAR IN 10

MONTH

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	
PRECIP	1.72	2.62	2.32	2.65	1.44	.36	1.56	.90	.46	.01	1.37	2.09	37.34	(in)
RUNOFF	.15	.59	.27	.54	.03	.00	.00	.00	.00	.00	.00	.01	10.61	(in)
CN	89.32	91.78	89.80	90.13	87.50	80.02	78.43	78.12	78.94	77.77	83.86	89.56	90.00	
MOIST	.44	.46	.46	.47	.46	.42	.39	.38	.38	.39	.40	.43	.43	
PL UP	.00	.00	.00	.01	.40	2.53	1.42	1.05	.61	.04	.03	.00	6.89	(in)
PERCOL	.07	.21	.21	.26	.08	.00	.00	.00	.00	.00	.00	.00	.58	(in)
SED YLD	.03	.08	.02	.33	.01	.00	.00	.00	.00	.00	.00	.01	3.50	(T/Ac)

Figure 2.--An example of a field layout and summary table constructed using the report generating microcomputer program for CREAMS model output files.

ARTIFICIAL INTELLIGENCE AND NATURAL RESOURCE MODELING

Kenneth G. Renard[1]

INTRODUCTION

Contrary to the impression which the title might convey, artificial intelligence (AI) has nothing to do with raising one's intelligence quotient so as to understand the complexities of the natural resource models which have been presented at this symposium. Rather, it is an exciting area of computer science research that has developed tremendously in the past decade, so that many practical applications may now be available.

Artificial intelligence research has several goals, including the development of computational models of intelligent behavior, both its cognitive and perceptual aspects (Duda and Shortliffe 1983). A more engineering-oriented goal of AI is the development of computer programs that can solve problems normally thought to require human intelligence. The field of AI consists of several areas, including speech recognition, language understanding, image analysis, robotics, and consultation or expert systems. This later area is the one with the most immediate applications (Michie 1983) in agricultural research and, specifically, natural resource problem solving. Potential applications of other AI areas may become apparent to most scientists in their own particular research programs.

EXPERT SYSTEMS

The goal of expert systems research is to provide tools that exploit new ways to encode and use knowledge to solve problems--not to duplicate intelligent human behavior in all aspects. The simplest, and generally the most successful, expert systems are classification programs. Their purpose is to weigh and balance evidence for a given case to decide how it should be categorized. Much effort may be needed to effectively implement an expert system. Thus it is necessary to constrain the expert system problem to a realistic one so that realistic solutions can be found to real-world problems.

The identification and encoding of knowledge is one of the most complex and arduous tasks encountered in the development of an expert system. And in fact, the very attempt to construct the knowledge base often reveals knowledge gaps in the subject, as well as weaknesses in available representation techniques. A major effort in the development of the expert system then is to overcome these gaps and to build a system where future knowledge can readily be inserted.

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One of the easiest ways to understand the use of expert systems is to think of some cases where you have had some experience with such a system. Duda and Shortliffe (1983) provide a list of 10 such systems. Certainly the one which my family doctor employs is the one I think of. My doctor is a member of the faculty of the University of Arizona Medical School but works at the Family Practice Center designed for training medical students. The Family Practice Center, located a few miles from University Hospital and most faculty members, is coupled to the computer at University Hospital. When problems of diagnosis arise, the doctor consults via a remote terminal with programs designed to assist with such diagnosis. Perhaps one program available is the MYCIN System developed at Stanford University in the mid-1970's to assist in the selection of antibiotics for patients with severe infections (Shortliffe 1976).

Those of you with VAX computers probably are aware that the physical layout and interconnection of the VAX components is done by using a rule-based expert system called XCON or RI (Duda and Shortliffe 1983).

Finally, I would be remiss if I did not mention that I first heard about AI and the development of expert systems from Dr. Gary C. White of the Environmental Sciences Group at the Los Alamos National Laboratory in New Mexico (personal communication). Dr. White recently proposed and has initiated with coworkers, the development of an expert system to provide consultation on the siting, design, and development of waste disposal facilities as well as for the construction and operation of such facilities. The expert system Dr. White envisions consists of the current information available to waste-disposal-site designers, as well as such computer models as CREAMS, for the design of the surface and near-surface facility and TRACER3D for that part of the disposal site further underground. The expert system envisioned will simplify the task of utilizing these computer tools by constructing the necessary input files and running the calculations with the program. The user, although aware that these computer models are being executed, would not need to be aware of how to operate the models himself. Model outputs would then become part of the expert system analysis. The expert system would assess the usefulness of an area as a potential site for waste disposal by comparing it to other currently operating sites as well as to a theoretically perfect site as a way to detect future potential problems.

The challenge then, is to apply the concepts of expert systems to other problems facing conservation planners in the agricultural sector. Some rather obvious applications are using USLE for conservation planning to meet soil loss tolerances, or using a combination of EPIC and CREAMS to ensure long-term soil productivity while ensuring that nonpoint-pollution problems and water quality standards are met. As in the waste disposal site expert system, the user might be requested to enter some basic information about the site being considered. Much of the data

required to operate the computer programs might then reside on disk files and not require keyboard entry. The results of the expert system might be a series of potential crop/management systems which might satisfy the environmental constraints.

SUMMARY

Although expert systems have not been applied to very many agricultural problems, and certainly not to many natural resource problems, their potential is great, and efforts along this line should be initiated. Much of the expert system research heretofore has been basic, but the field is beginning to make the transition to application and especially in the area of planning and design. It seems likely that the inclusion of economics in some design problems will add a further dimension to the utilization of expert systems.

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ARS/SCS NATURAL RESOURCES MODELING SYMPOSIUM SUMMARY COMMENTS OF SCS

John L. Okay*

We view this symposium as a milestone in coordination between ARS and SCS. The tone in all sessions has been positive, and a frank exchange of ideas has led to better understanding of the needs of both agencies. We look forward to a continued growth of cooperation in model development.

Technology transfer has been discussed in every session. We feel this is a must if research is to become useful to a service agency such as SCS. SCS needs to fully support the research that ARS is doing; at the same time, we need to accept our responsibility to develop operational versions of the various models for our field people. Technology transfer requires input from staff at all levels and locations. Each agency must ensure that it coordinates its efforts with the appropriate personnel in the other agency.

Natural resources modeling is an emerging field and it suffers from lack of clear definitions in some cases. We need to avoid this confusion. We have heard various models described this week, and at times it has been difficult to distinguish between different models and different computer programs for the same model. We need to be careful not to confuse models and computer programs. It will be much easier to determine the differences between similar models and the similarities between different models if the problem is not confused by mixing similarities and differences in computer coding.

SCS needs models to aid in making policy decisions and technical decisions at many levels within the agency. These models must be scientifically based tools. Much of the work that ARS is doing will help provide the models we need, but there are some areas that require more attention to make the models being developed more useful to us.

First, the carefully conducted research of ARS scientists in many cases has produced two or more models for the same process. Are all these models equally good? If so, why use one instead of another; if not, which one is better and why? Is it just a matter of personal preference, or are there valid technical reasons to select one model over another? If it depends on where and how a model is to be used, we need more information on model limitations. ARS should help us select "best" models for technology transfer.

Second, validation of models has been discussed in every session, but no criteria for validation have been specified. We must remember that calibration is not validation. We urge ARS to establish validation procedures and criteria. Objective and uniform validation is the best quality assurance tool in the difficult task of developing from complex research models the operational models SCS needs. The comprehensive research model must be validated before it is simplified, or generalized, for field operations use; and the operational model must also be validated and the computational procedures verified so we can determine the sacrifices in accuracy for gains in efficiency. A comprehensive validation procedure is needed at every step because a simple model built on experience and judgment but not fully validated is not ready for use even though it could be easily implemented at the field level.

Third, SCS needs models that utilize exisiting data. For models developed in the future, we need enough lead time to begin assembling the required data. With the extensive data required to run most of the research models, we must be concerned with the sensitivity of the model results to variations in the input data. If we need data we are not collecting, we must collect them. If we are collecting data we do not need, we should stop collecting them. We should also spend the most effort collecting the data that are the most important in terms of model sensitivity.

We are encouraged by the participation in this symposium. We look for the directions established here to influence the development of models in the future. The clearer understanding of the needs and responsibilities of both agencies will lead to model development in a true partnership atmosphere. Each of us is responsible for working toward maintaining this partnership.

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SCS OVERVIEW OF CHEMICAL AND BIOLOGICAL PROCESSES

L. Dean Marriage[1]

"There is urgent need to balance the value of using the most efficient and economical agricultural practices . . . and the value of maintaining or improving wherever possible the quality and quantity of fish and wildlife habitats . . ." This statement comes from "Impacts of Emerging Agricultural Trends on Fish and Wildlife Habitat (1982)," a report prepared at the request of the National Research Council and reviewed by the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine. The report further states, "The biological value of wildlife and its habitats is derived from their contribution to genetic research, their potential for providing now unknown benefits in the future, and their crucial role within their delicately balanced ecosystems." The report concludes that, "The agriculture and forest industry is the largest modifier of the lands and waters that provide habitats for fish and wildlife."

The presence (or absence) of fish or wildlife and their habitats is a valuable indicator of the overall environmental quality. Predicting the impact of man's use and management on our land and water resources and these ecosystems are generally what we will be addressing today. The clearer our understanding of how the components of the ecosystem (plant, animals, soils) interact under different levels of management, the better will be our ability to evaluate proposed land use alternatives.

I think it well to recognize that there has been a communications problem between SCS managers and ARS researchers. For example, SCS biologists have frequently asked ARS the question, "What is the effect of sediment on fish production?" ARS, however, has not assigned the question high enough research priority to provide the answers that SCS needs. This is a communications problem and is probably as much SCS' fault as ARS', if not more so. SCS should be more specific and break down the question as follows:

1. Given the erosion rate in the watershed, how much sediment is delivered to a stream?
2. What proportion of the sediment is bed material?
3. How much of the sediment is suspended?
4. When is sediment moved in time--daily, weekly, monthly?

The answers to these kinds of questions will allow the biologist to identify the impacts of sediment on the aquatic environment and then determine fish production. At each of their developmental stages, fish have different life requirements, and knowing when sedimentation is most likely to occur, therefore, is of paramount importance. An adult fish can be extremely tolerant of high sediment concentrations, but an embryo is very sensitive. Average annual sediment yields simply are not sufficient to determine impacts of sediment.

We must give more attention to density (organisms per unit area), richness (number of species), and dynamics of natural communities. Understanding the dynamics of natural communities, for example, is critical if we are to protect the habitat of animals, such as sage grouse, which depend upon distinct seral stages of plant communities. The Western Association of Fish and Wildlife Agencies recognized this in its "Guidelines for Maintenance of Sage Grouse Habitats" (Braun et al. 1977) prepared for those proposing to manipulate sagebrush communities. One of the guidelines specifies that "no control work will be considered where live sagebrush cover is less than 20 percent or on steep (20 percent or more gradient) upper slopes with skeletal soils where big sagebrush is 30 cm or less in height." These vegetative conditions represent a mid- to late-successional (seral) stage which is the only stage suitable for sage grouse. Given adequate field observation data, a model could be constructed that would aid planners in determining when and where the plant community meets these specifications.

When we at SCS ask ARS researchers to help us determine the effects of new grazing systems on wildlife, we must ask such specific questions as--

1. What effect does grazing at high intensity, short duration have on soil compaction and plant production?
2. What changes will occur in plant communities over time as a result of this type of use?
3. How much sediment is produced and delivered under known rainfall events, and when?

Answers to these questions will allow the biologist to further his efforts in determining animal population response and estimate the effects of grazing systems on wildlife. Broad, general objectives such as range improvement are good objectives, but not all range improvement practices are unilaterally beneficial to all wildlife species. The impacts on wildlife habitat of each range improvement practice must be clearly understood if we are to intelligently recommend range management alternatives to the public and if we are to evaluate national programs. To do this, however, will require identifying and evaluating physiochemical processes and other cause-and-effect mechanisms--something we have been neglecting!

Long- and short-term effects of erosion and land management practices on fish and wildlife frequently require temporal analyses. Average annual values for erosion such as those calculated by USLE are of limited use. For biologists to predict fish and wildlife response to problems and treatments, it is often necessary to reconstruct historical information to calibrate

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population models. Since USLE provides a long-term average (tons per acre per year), these values may not be representative of any given year or event within a year, and correlation with other information such as population data may not be possible. These kinds of analyses can be made, however, by knowing how much sediment is produced and/or reaches the stream when spring planting, fall plowing, or other management activity takes place at different stages of crop growth.

We have been too shortsighted in recognizing habitat structure needs for animals or groups of animals. For example, Thomas (1979) identified six species of birds in the Blue Mountains of Oregon and Washington that reproduce in bushes and feed in trees, bushes, or the air. In this case, if the bush structure was altered or destroyed, reproduction of these birds in this area would cease and they would be forced to seek nesting outside the area. They might, however, make short feeding excursions from their newly found nesting areas. How will land management practices effect this habitat structure? Do we need to manage for a particular seral stage that will provide the necessary habitat structure?

Pesticides are being applied at ever-increasing amounts for agricultural purposes. In excess of 59,000 metric tons of insecticides, 169,000 tons of herbicides, and 3,500 tons of fungicides were applied to the United States in 1976 (National Research Council, 1982). How are these pesticides being cycled in the food webs? What do we know about their bioconcentration in the plant-soil-animal complex? How many, in what chemical form, and in what quantity are pesticides reaching our surface and ground waters? What are the impacts of increased use of fertilizer and pesticides on fish and wildlife as a result of no-till? Can such questions be addressed through modeling?

The concentration of toxic substances in the body is well documented for some animals. For example, the storage and concentration of DDT in fatty tissues of birds has been demonstrated. High levels of DDT in the fatty tissues of robins and sparrows do not kill the birds directly until they are forced to use their fat reserves during the winter, when food is scarce (Bernard 1963).

Let us briefly turn our attention to a unique ecosystem--wetlands. Recently a more diverse set of wetland values has been recognized, including flood conveyance, flood storage, storm and erosion control, pollution control, water supply, oxygen production, recreation, fish and wildlife habitat, education, and scientific study. What role does the wetland play in the hydrologic system? Can models be developed to explain this role and predict impacts when wetlands in a watershed are lost? Is there potential danger of contamination of water supplies? Will wetland alteration cause increased flood damage to upstream, adjacent, or downstream properties? Will alteration destroy plant and animal life important to coastal or inland fisheries or migratory waterfowl? Can questions such as these be answered through modeling?

USDA's National Conservation Program (NCP) establishes six long-term conservation objectives:

1. Reduce excessive erosion.
2. Improve irrigation efficiency.
3. Improve water management.
4. Reduce upstream flooding.
5. Improve range condition.
6. Improve water quality.

Chemical and/or biological processes can be read into each one of these objectives. For example, reducing excessive erosion in a watershed will very likely reduce sediment delivered to streams and wetlands. It is possible we might model siltation perturbations that are reduced in these aquatic habitats. What happens to water supplied to certain wetlands when irrigation efficiency is improved? We are often asked this question by planners working with the Colorado River Basin Salinity Control Program. Can we track water supplies to the wetlands through models?

The SCS's 1983 "Soil and Water Conservation Research and Education Progress and Needs Report" identifies eleven research topics needing highest priority (SCS 1983):

1. Erosion-soil productivity relationships.
2. Conservation tillage.
3. Concentrated flow erosion prediction.
4. Crop production systems for areas with limited water supply.
5. Net economic benefits of conservation practices.
6. Gully prevention and control.
7. Effects of new grazing systems.
8. Improving use of USLE for rangeland.
9. Socioeconomic factors affecting adoption of conservation practices.
10. Improved spillway design.
11. Water quality research.

It does not take very much examination to realize that chemical and biological processes are an integral part of nearly all of these. For example, economic evaluation of fish and wildlife resources has not been possible because we lack operational tools (data bases and models) to perform them. Sufficient economic values for fish and wildlife have not been identified and correlated with population dynamics. Current economic values deal with recreational or commercial use of the resource and are generally limited to those fish and wildlife species with recreational or commercial value. What is the true value of a deer, a trout, or a mourning dove? Can a value be assigned to nonconsumptive uses of wildlife such as birding and scientific and educational uses? The U.S. Fish and Wildlife Service explored some of these things in their 1980 Fishing and Hunting Survey. How can we model these values to give planners (economists) the guidance they need?

Our primary charges at this symposium are to examine the state of the art in concepts and natural resource models and to assess the highest priority needs of both agencies. SCS needs to relate basic research to the development of practical, operational models that field-level personnel and others need to help them in conservation planning.

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ARS OVERVIEW OF CHEMICAL AND BIOLOGICAL PROCESSES OF NATURAL RESOURCE MODELING

R. F. Follett[1]

This workshop has been divided into four concurrent sessions on a) chemical and biological processes, b) soil-water-plant relations, c) hydrology, and d) erosion. Although this was necessary because of the breadth and number of topics that need to be covered, we must recognize that there are strong and important linkages required across all four concurrent sessions.

The Agricultural Research Service (ARS) has been conducting research on chemical and biological processes for some time in accordance with several legislative mandates. Perhaps some background information on the origins of these mandates would be useful at this point. A symposium sponsored by the American Association for the Advancement of Science was held in 1967 and described agriculture's relationship and research role in environmental quality. The symposium included discussions of livestock wastes, sediment, nutrients, and pesticides (Brady, 1967). Even though the nature of agricultural pollutants was established as far back as 1967, serious attention to the impacts of these pollutants in the United States was not forthcoming until passage of the Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500), particularly Section 208. The P.L. 92-500 helped establish cooperation among several Federal agencies, including ARS and SCS, for conducting research, investigations, training, and information programs for preventing and reducing agricultural pollution. The Safe Drinking Water Act of 1974 (P.L. 93-523) indicated to water resource managers that a wider range of potentially toxic substances should be monitored and that perhaps epidemiological studies should be initiated to assess long-term health implications. The Toxic Substances Control Act of 1976 (P.L. 94-469) further emphasized the concerns with the presence of toxic materials in the environment. The Clean Water Act of 1977 (P.L. 95-217) amended Section 208 of P.L. 92-500 and authorized the Secretary of Agriculture to establish and administer a program to control water pollution from nonpoint sources. Although the Act called for an extensive program, planned funding was slow to materialize. Finally, Congress appropriated about 10 percent ($50 million) of the planned level of funding to USDA in FY 1980 to initiate the Rural Clean Water Program (RCWP) on an experimental basis. Congress then added another $20 million in FY 1981.

One of the most important recent legislative mandates is the Soil and Water Resource Conservation Act (RCA) of 1977 (P.L. 95-192). The RCA provided that the Secretary shall appraise, on a continuing basis, the soil, water, and related resources of the Nation, as well as to develop and periodically update a program for furthering their conservation, protection, and enhancement. Furthermore, it is recognized in the RCA that agricultural activity may be the most widespread potential source of nonpoint-source pollution for increasing the levels of bacteria, sediment, nutrients, and pesticides in U.S. waters.

Thus, besides a continual progression of agricultural research contributions to environmental quality, there have also been a corresponding progression of legislative mandates concerning the role of agriculture in environmental quality.

As is indicated in its title, this symposium focuses on natural resources modeling. Modeling is an essential feature of systems science and ranges from mental models to quantitative models that can be used for predictive purposes. For the planning and implementation of natural resource programs within USDA, quantitative evaluation of the chemical and biological systems often requires mathematical modeling. As numbers of variables increase, the models become more and more complex and require larger numbers of coefficients. Consequently, even though models are considered as primarily a tool, they and computers are a necessity for defining the highly complex processes and interrelationships that are involved.

Models are essential for the evaluation of responses of natural systems to changes in management practices for large areas of land.[2] Data can be provided for a wide range of soils, climates, topography, and other factors that could never be collected. For example, it would never be practical to monitor the movement of chemicals and sediment from every field in the United States. However, data already available on rainfall, soil properties, topography, and management practices can be fed into models that simulate chemical, physical, and biological processes and generate outputs showing the movement of chemicals and sediment under different conservation practices. If the models are validated for selected areas in a land resource area where data on chemical and sediment movement are available, then we can be confident that the model can, within certain limits, produce accurate simulated data for those broad areas where data are not available. This is just one example of the kind of data that can be produced by well designed and tested models.

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2/ Recognition is given to Dr. Harry Pionke (ARS, University Park, PA), Dr. Donn DeCoursey (ARS, Ft. Collins, CO), and Dr. Clarence Lance (ARS, Durant, OK) for their discussions and ideas that were used to help develop the following perspectives on modeling and scientific issues related to modeling.

The ARS, as a research agency, has a definite role in modeling and in meeting the needs of SCS, as an action agency. The ARS has had and will continue to have a role in the development of user-oriented models. However, as a research organization interested in modeling, emphasis within ARS is on research models that describe and communicate processes and test hypotheses. Where unifying concepts are the focus, the net result may be the convergence toward a single unifying model. On the other hand, objectives of an action agency may be quite different. Models are needed by SCS and other action agencies for management purposes. Models designed to achieve user objectives may not unify but, instead, may divide modeling efforts into discrete problem areas.

Thus, where researchers might converge on a single or fewer models, SCS or other action agencies may need several different models, depending on their particular management objectives and the application for the model(s). A primary interest for users are the underlying concepts needed to achieve specific user objectives. Because concepts are the base upon which different user-oriented models are built, chemical and biological systems must emphasize individual processes and their rates. Those of us in research must also be aware of one of the findings in a recent Office of Technology Assessment report (1982) that "by concentrating primarily on research needs, it misdirects agency priorities toward research per se rather than toward coordinated development and utilization of scientific knowledge and related analytic capabilities". Modeling efforts are one of the best available alternatives for analyzing complex natural resource problems and helping to focus and increase the efficiency of the use of agency resources for solving complex national problems.

A final point is the special needs of user-oriented models for data sets. The need for data generally falls in the following two categories:

First, model development needs input data to provide simulations for establishing mathematical relationships and coefficients. On experimental sites, these data can be experimentally defined and determined. In the field, under agricultural, range, or forested conditions, input data are not determined experimentally because they are too costly. Instead, low cost, reasonably accurate methods are devised to estimate input data. For the chemistry/biological models, few data are available.

Second, there is a special need for data sets that can be used to validate user-oriented models before they are applied. Essentially, validation means comparing model output to an observed data set for conditions for which the model is to be applied. This is a critical step and often there is little available data. Also user application and condition of use may influence the choice of data sets for validation. With the exception of the paper elsewhere in this volume by Dr. Bill Spencer, few deal with validation data sets.

Although much could be said about past ARS accomplishments in modeling chemical and biological systems, many of you are far more familiar with these efforts than I. It is sufficient to indicate that current ARS efforts generally emphasize nitrogen and phosphorus more than salinity and pesticides and that biology is the least emphasized. Perhaps with the use of priority setting processes at this and possible future meetings, this emphasis will shift or new areas will be identified. Irrespective, the accomplishments of ARS in the area of natural resource models are significant. Among the natural resource models to which ARS has contributed are CREAMS, EPIC, SWAM, SWRRB, NTRM, and others. These models can provide either input information or working subroutines for the Soil and Water Conservation Assessment Model (SAWCAM).

I have reviewed the background material on SAWCAM and recognized a number of important concepts. However, I also noted some aspects that perhaps are missing and that eventually will be important to SAWCAM. In addition, a need exists for mutual reinforcement and mutual benefit between experimental data collection and modeling efforts. There is also a need to recognize the interconnectedness of natural resource systems and how extensive the implications of soil and water management practices are. I will give two examples--first, one on biology and then one on chemistry--to illustrate the increasing complexity required for modeling efforts to describe the interrelationships between agricultural activities on the land surface and eventual impacts on other systems. At least conceptually, future user-oriented modeling efforts in support of SAWCAM should be more forward-looking and conceptually holistic.

Biological - The activities of man on the surface of the land, such as intensification of agriculture, deforestation, and urbanization can modify the cycles that couple land and water. Many of these activities contribute directly to accelerated nutrient cycling and transport of sediment. The hydrologic regime is typically seen as a distribution network by which materials are transported from one reaction site to another. However, we must avoid treating streams, lakes, and reservoirs as passive or inert conduits. Those parts of our river and stream network closest to the impacts of what is done on the land are often upstream aquatic ecosystems which have a large biological component. They include farm ponds, impoundments, buffer strips, and wetlands. These all can be utilized more extensively than we do now to manage water quality. Nutrients, farm chemicals, and sediment are carried in runoff as it moves from farm fields through these upstream ecosystems to streams, lakes, and reservoirs. In each part of this hydrologic network are many kinds and rates of reaction between dissolved and suspended materials in the waters and the "walls" of the conduit. For example, the walls of a river include algae and other aquatic plants and the animals that live there.

When the biological component is considered in this network, there are considerable economic consequences that should be considered as part of the costs or benefits of conservation and other practices on the land. It is not my intent to emphasize fish in my discussion. However, sport and other fishing do represent a major economic enterprise in parts of the United States. Soil erosion resulting from improper land management practices can directly contribute to reduction in aquatic habitat and populations. When sedimentation of gravel substrates in streams and rivers used for spawning beds occurs, the amounts of fines are increased in the gravel interstices and the flow of water through the gravel is reduced. Available oxygen becomes limiting; toxic wastes accumulate and increase; temperatures change; and, if the embryo has survived, the difficulty for fry emergence is greatly increased once they are hatched. Thus, the impact of soil erosion from farm fields or other land surfaces and the movement of sediment and associated chemicals can have a vital economic impact on aquatic biology. As a specific example of the economic costs, thermal effects resulting from the loss of riparian vegetation alone in the Tucannon River Watershed in Washington State, are reported elsewhere is this volume by Dr. Fred Theurer to be $1.1 million (average annual). In addition, almost one-third of the river no longer supports spawning because of a combined thermal and sediment problem in the substrate. If the damages for only thermal effects from the watershed of only one river are that large, then how many millions (or perhaps billions) of dollars of damage are occurring nationally to aquatic habitat and biological systems due to thermal, sediment, and other problems? Should not these effects also be considered as part of the cost of soil erosion? In addition, this is but one of the biological impacts that should be considered. It follows, therefore, that our natural resource models eventually need to describe these complex and interrelated systems, including the impacts of land management practices on biological systems. Such models would provide information for improved resource management, economic analysis, and policy decisions for U.S. agriculture.

Chemical - There are also other serious needs in our research and modeling efforts on chemical processes. Some may become critical issues that both research and action agencies must address in the very near future. However, the level of understanding, adequacy of data, and procedures to address certain of these issues may not yet be available. An assessment of the necessary research and modeling capabilities is needed. I will use the issue of groundwater quality to demonstrate how agricultural activities may significantly influence a major natural resource.

Estimates are that nearly one-half of the population of the United States use groundwater from wells or springs as their primary source of drinking water (Water Resources Council, 1978). About 65 percent of the estimated 88.5 billion gallons per day of fresh groundwater withdrawals in 1980 were used for irrigated agriculture.[3] There is a very close interrelationship between surfacewater and groundwater supplies since surface waters provide groundwater aquifer recharge. At the same time estimates (Water Resources Council, 1978) are that 30 percent of the streamflow in the United States is supplied by groundwater. Groundwater contamination may occur naturally, such as the natural contamination of groundwaters from uranium-caused radioactivity in Texas, Oklahoma, and New Mexico.[3] However, there is increasing evidence of groundwater contamination resulting from man's activities. These sources are summarized in a recent review article by Pye and Patrick (1983) and include manufacturing and service industries, agriculture, domestic wastes, and wastes resulting from government activities. In terms of evaluating our capabilities within USDA and ARS, a significant contribution on the part of USDA might be in understanding the impacts of loading rates attributable to agricultural activities. Cooperation with other appropriate Federal and State agencies or institutions may be especially advantageous to all in terms of following the impacts of agricultural practices on the land surface, through the root zone, into the vadose zone, and then into the groundwater. The quality of water drawn from wells is of vital concern to the millions of people who depend on these supplies for their drinking water, for irrigation, and for industry. Because subsurface waters are usually derived from surface waters at some time in the past, their chemical compositions carry the stamp of their origin at the surface as well as of their underground passage through soils and rocks.

Pye and Patrick (1983) summarized the most frequently reported sources of groundwater contamination in the 10 States that had the greatest amounts of information. Interestingly, the States reported were from nearly all parts of the United States and all reported occurrences of agriculturally related contaminants. Where the source of chemical substances is anthropogenic and reflects the types and extent of human activities, it is not enough to merely follow the pathways to the groundwater. Instead, practices to change or alter these pathways must be identified. If the source and loading rates of potentially harmful chemical substances are primarily from agriculture, then effective soil and water conservation or management practices need to be devised and applied to try and correct the problem. Contaminants moving from the ground surface to groundwater can be attenuated by both physicochemical and biological processes. However, once contaminants reach the aquifer, the potential for their attenuation by biological processes is much reduced.

I believe that the above two examples illustrate the need to be forward looking and to evaluate our current state-of-the-art knowledge at this

3/ U.S. Geological Survey (USGS), Reston, VA. Preliminary unpublished data from the National Water Use Information Program (1982).

symposium and to strengthen our ability to describe those processes. Yet, we should not hold to the goal of understanding in detail every watershed in the world with respect to every possible chemical and biological system. Priorities must be established and workable and economic approaches developed. The quantities and distribution of chemical substances must be described as they influence the productivity and quality of the natural resources important to and impacted by agriculture. Once it is known that a clearly deleterious substance has invaded the system and the load is defined in terms of sources, pathways, and sinks, methods and practices must be devised to intervene intelligently. We need to give careful consideration to working with our action agency partners in USDA and with other Federal and State agencies.

The following four items paraphrase or quote some of the highest priority scientific issues that need to be addressed, as they were recently summarized by DeCoursey:[4]

1. How can chemistry and biology be coupled with our understanding of physics of water and sediment movement? How can this understanding be applied to the management of groundwater and surface-water quality?

2. What is the impact of toxic substances in the food we eat or in the water we drink ... and ultimately, on human life? Do long-time horizons, explicit in the migration of toxic substances, impose the need for new methods of risk assessment?

3. Given various theoretical models, what advances and techniques are needed to measure and define statistically stable estimates of the requisite parameters? Are existing data sets adequate for both causal and statistical usage? What are the costs and time requirements for obtaining the needed data sets?

4. Can models of sequentially dependent processes be linked satisfactorily to form a causal chain of understanding leading to optimal control and predictive power necessary to address relevant societal issues? Can existing data bases be manageably integrated to formulate and calibrate such chains of models and their parameters?

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I look forward to open and constructive discussions throughout this session and to meeting the objectives outlined and mailed to each of us prior to our coming here.

As we go forward with this session, the concerns and needs of our action agency partners provide those of us in research a particularly valuable source of information and direction as we continue to develop our programs.

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USE OF SORPTION ISOTHERMS TO CHARACTERIZE STREAM TRANSPORT OF P IN WATERSHEDS

Harry M. Kunishi and Harry B. Pionke[1]

INTRODUCTION

Models describing the transport of P from such areas as agricultural fields and watersheds continue to be reported. Most of the models presently in use, however, apply to systems of streams that carry P primarily in either the liquid phase or the solid, suspended phase. For the former systems, the amount of P transported is estimated from P in solution. For the latter, the estimate is based on the product of the suspended load times a P coefficient of partition between the liquid and solid phases. Corrections are sometimes included to account for the apparent P enrichment of the suspended phase due to deposition of the coarser, P-poor particles.

We have developed a model to describe P transport by stream systems that contain significant amounts of P in both the liquid and suspended phases. The model considers the fact that in such systems, the concentrations of algae-available P in these two phases are mutually dependent, governed by a near equilibrium relation; the fact that soils, which may differ in physical and chemical properties, enter the system at numerous different points to add to the suspended load; and the fact that with each entry, changes take place with respect to the amounts and kinds of soil borne in suspension, the P enrichment level of the suspended phase, and the P distribution between the suspended and liquid phases. Details of the computerization aspect of the model, developed in conjunction with the SWAM project, are reported in Pionke et al. (this volume). The theoretical considerations of our modeling approach are reported below.

Relation Between Soil P and Solution P

In soil systems (soil plus moisture up to field capacity) the relationship between P in solution and P on the soil surfaces is complex. An excellent review of the findings was recently presented by Olsen and Khasawneh (1980). The complexity of the relationship is due to a number of factors. Soils are composites of widely different primary and secondary minerals. Acid soils react differently from calcareous soils; moreover, among acid soils, those rich in the oxides of Al or Fe behave differently from those poor in these oxides. The behavior of P in soils rich in organic material is not well understood. At very high P loadings in soil systems, P levels in solution may be controlled by P precipitating onto or dissolving from crystalline surfaces of P compounds. At low P loadings, P levels in solution, like those within the region of agricultural interest (that is, between 0 and 0.5 ppm), will likely be controlled by adsorption-desorption phenomena. Mathematically describing these phenomena is difficult because P binds over different ranges of energies depending upon its fertility level.

Despite these complicating factors, Schofield (1955) related P in solution to P in the soil by an equation that has been accepted as one that meets rigorous thermodynamic standards. He argued that in a soil system with Ca as the predominant cation, (1) the equilibrium phosphate potential (EPP) can be defined as equal to $-\log_{10}$ ($a\ Ca^{\frac{1}{2}} \times a\ H_2PO_4$), (2) the value of EPP does not vary in space within the soil system, and thus (3) single measurements of Ca and P in the solution phase will uniquely define the P enrichment status of the soil system.

P Sorption Isotherms

Beckett and White (1964) used Schofield's equation in plotting P sorption isotherms for several soils. Presenting thermodynamic justification, they showed that in an isotherm like those they obtained, the intercept on the Y axis is a measure of the pool of labile P, or net exchange sites, associated with the soil and the slope of the curve (Q/I) a measure of the soil's capacity to buffer the concentration of P in solution. (Both measures vary, however, in accordance with the duration selected for equilibrating the soil-plus-solution mixtures used in determining the isotherm.) In contrast to the Beckett and White isotherm, the Freundlich isotherm, $q = ac^b$ (where q is the quantity of P adsorbed, c is the P concentration in solution, and a and b are constants), appears less useful in its original form because it ignores the pool of native P. The Langmuir isotherm, $q = kbc/(1 + kc)$, where k is associated with the energy of adsorption and b represents the maximum adsorption possible, appears inconsistent with soil P sorption characteristics because it requires uniform adsorption sites, maximum adsorption corresponding to complete monolayer coverage, and so forth. A more comprehensive review is presented by Olsen and Khasawneh (1980).

Taylor and Kunishi (1971) extended the concepts presented by Schofield (1955) and Beckett and White (1964) in applying them not only to soil systems but also to stream sediments and suspensions, which are associated with large volumes of water. Additionally, they simplified the chemical analysis by monitoring only the concentration of P rather than both the concentrations of P and Ca. In their P sorption isotherms, the point analogous to EPP was called the equilibrium phosphate concentration (EPC), and the Y intercept and the slope were considered indexes, respectively, of the soils' pool of labile P (P_I) and buffering capacity

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(fig. 1). They used this empirical approach in determining the P sorption characteristics of samples taken from a small watershed (26 km^2) in central Pennsylvania. The simplicity of their approach and the size of the watershed they studied prompted us to use their data for our modeling effort. Henceforth in this report, the term "P sorption isotherm" and related terms (for example, "P_I," "buffer capacity") are defined according to these researchers.

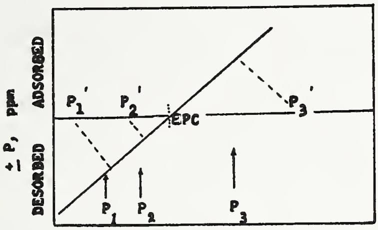

Figure 1.—Features of a sorption isotherm. For its construction, soil samples of equal weight are equilibrated for 24 h with identical volumes of aqueous solutions initially differing in P concentration (P_1', P_2', P_3'). The final concentrations of solution P (P_1, P_2, P_3) are determined and plotted against $\pm$ P values which are the amounts of P adsorbed or desorbed by the soil (the differences between the final and initial values of solution P). EPC is the equilibrium phosphate concentration, the concentration at which the solution neither gains nor loses P to soil. P_I, the extrapolated intercept on the Y axis, and the slope of the curve are considered as indexes, respectively, of the soil's pool of available P and ability to buffer P concentrations in solution.

Sorption isotherms of the type determined by Taylor and Kunishi (1971) are curvilinear, particularly for soils excessively fertilized with P or for any soil if determined over an extended range of solution P (fig. 1). For this reason and the fact that the isotherms are based on phosphate concentration rather than potential, the validity of using P_I as an index of labile P may be questioned. Data recently obtained by Wolf et al. (this volume), however, showed that when the P fertility levels of the soils were like those of the samples examined by Taylor and Kunishi--that is, within the range of agricultural interest—(1) the sorption isotherms were nearly linear over the range of solution P concentrations pertinent to our modeling purposes (that is, a range of concentrations straddling EPC but primarily lower than EPC) and (2) P_I was well correlated both with labile P as measured by isotope dilution and with resin-extractable P. For such soils, therefore, it would appear that their P sorption characteristics may be determined on the basis of phosphate concentration and their sorption isotherms used for the following purposes, all of which are highly relevant to our modeling effort: inventory the amount of adsorbed P having the potential to be desorbed, predict the level of P in solution at any given soil-to-solution ratio, quantify P in solution and P adsorbed on the soil, and monitor the movement of P from one phase to another as ambient conditions change.

Taylor and Kunishi (1971) determined the sorption isotherms for samples of soil and stream sediment collected from various parts of Pennsylvania's Mahantango watershed. Although the samples represented different soils and their mixtures, the isotherms formed a pattern of curves related through their slopes. This family of curves suggested that P sorption was controlled by the same mechanism in all the samples. The researchers then selected two of the samples—one of which was high and the other low in P enrichment--mixed them in different ratios, and determined the isotherms of the mixtures. These isotherms fell between those of the component soils, a result suggesting that the sorption isotherms of both sedimented and suspended materials in streams could be predicted if the amounts and sorption characteristics of their component soils were known. The fact that the isotherms of the mixtures were not weighted averages of the component soils' isotherms indicated that when the mixtures were formed, P was redistributed between the component soils partly in accordance with their P fixation potential.

APPROACH

The findings of Taylor and Kunishi (1971) led us to consider the Mahantango soils as consisting of one type regarding the mechanism for controlling P sorption, and to seek two pieces of information on that soil type: (1) an equation describing how its sorption isotherm changes with changes in P fertility and (2) its P fixation coefficient. We called the equation the controlling equation. With these two pieces of information we could predict the P sorption characteristics of any stream sample within the watershed if we knew the amounts of the component soils it contained. By predicting the sorption characteristics of stream samples, we could, in turn, predict P transport in the watershed. Models for prediciting the amounts of component soils present in stream samples are under development by other researchers in the SWAM project.

Controlling Equations

Using Taylor and Kunishi's data (1971), we calculated the controlling equation to be P_I = 69.3 EPC + 3.2. The geographical extent to which this equation applies may be tested, beginning with soils in areas adjacent to the

Mahantango watershed and continuing with soils in progressively farther areas.

Controlling equations must be determined experimentally; they cannot be deduced from the known properties of soils, because those that influence P sorpton and fixation are not understood in well enough detail. At present, there is no broad data bank of P_I and EPC values.

In a study of four southeastern soils, Kunishi et al. (1979) found that lime, as well as P, applications affected both the amount of resin-extractable P and EPC. These two parameters were linearly related by the equations shown below (table 1) when the P fertility levels of the soils were in the range of agricultural interest.

Table 1.--Controlling equations (labile P vs. EPC) for four southeastern soils, each from a different watershed

Soil	Clay	$Al(OH)_3$	Equation
	%	%	
Evard	33	40	Y = 501X + 47
Brevard	15	23	Y = 158X + 47
Lucedale	27	1	Y = 248X + 60
Luverne	12	1	Y = 99X + 50

In the equations, Y = resin-extractable P and X = EPC. Because resin-extractable P is an index of the pool of labile P, Y = P_I also. (As shown in figure 1, P_I is the intercept on the negative part of the Y axis, which represents P desorbed by the soils.) When P_I is substituted for Y in the equations, they are readily recognizable as controlling equations. Thus a family of sorption isotherms may be drawn for each of the southeastern soils. The relation between these isotherms and the straight line described by the equation for resin-extractable P and EPC may be shown pictorially as in figure 2.

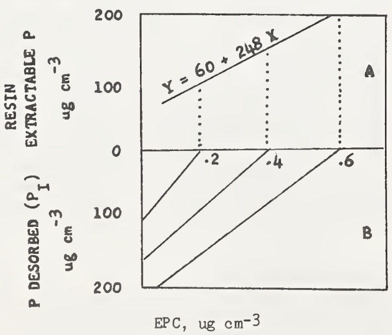

Figure 2.--For Lucedale soil: plot (A) of resin-extractable P vs. EPC juxtaposed to plot (B) showing the soil's desorption characteristics. Both plots are related by the equation shown.

Although these soils were taken from the Southeast, they derived from widely separated watersheds. Also, they fixed different amounts of P, apparently because they contained different levels of aluminum oxides and clay. As might be expected, therefore, the controlling equations for these soils are different.

Equations closely approximating controlling equations for other soils may be gleaned from published information. For example, a report by Olsen and Watanabe (1963) on some western soils showed that labile P determined with ^{32}P was linearly related to solution P when the P enrichment levels of those soils were in the range of agricultural interest. The linear equations may be considered controlling equations because the solution P values closely approximated EPC values. Thus, families of isotherms may be drawn for these western soils also by the method described above for the southeastern soils studied by Kunishi et al. (1979). State soil testing laboratories routinely analyze soil P by chemical extraction and calibrate the assays with crop yield data in field-plot tests. These laboratories do not routinely determine P sorption isotherms. Partly in response to this deficiency, Wolfe et al. (this volume) determined the sorption isotherms of a broad range of soils and compared the P_I and EPC values with data obtained for the same soils by the State laboratories. They found that certain data obtained by these laboratories may be used as close approximations of P_I and EPC. Controlling equations can be calculated from these data.

Data from the sources cited above in connection with controlling equations provide evidence that for soils of similar type with P fertility levels within the range of agricultural interest, EPC is almost linearly related to the following indexes of the pool of labile P: P measureable by isotope dilution with ^{32}P, resin-extractable P, and P_I.

P Fixation Coefficient

The P fixation coefficient (FC) is used to calculate the amount of freshly sorbed P that is made unavailable for easy release. This parameter for the Mahantango watershed soils was determined from Taylor and Kunishi's (1971) sorption isotherms for Lo-P and Hi-P soils and their mixtures. As an example, when a low P soil (A) is mixed with a high P soil (B) at a 1:1 ratio, the new intercept ($I_{A:B}$) is calculated via the following equation:

$$P_{I_{A:B}} = P_{I_A} + \left(P_{I_B} - \left(P_{I_B} - P_{I_A}\right) FC\right)/2, \qquad (1)$$

where the subscripts identify the soils and FC refers to the fixation coefficient. FC operates on the difference in intercepts for A and B (labile P pool, A vs. B), and therefore the amount fixed depends not only on FC but also on the separation of the two labile P pools.

P fixation coefficients may be determined experimentally by other methods. For example, Kunishi et al. (1979) amended each of the four southeastern soils mentioned previously with known amounts of P and then extracted P from the soils with a resin. The percentages of added P that could not be recovered from the soils were the percentages fixed. In studying the four soils, the researchers first limed each one at four different levels; then, within each lime level, they applied P at four different rates. They found that within each lime level, the percentage of P fixed decreased with the rate of P application. The decreases average 6, 9, 14, and 34 percent, respectively, for the Evard, Brevard, Lucedale, and Luverne soils over the four levels of P addition. For three of the four soils, therefore, variability in the percentage of P fixed may not be high enough to discourage the use of one constant value for the P fixation coefficient.

Computer Modeling of Sorption Isotherms

We designed the computer program so that, given the experimentally determined P fixation coefficient of the soil type and the P_I values of the lowest P soil (A) and the highest P soil (B), the computer calculates the P_I values of certain key mixtures of A and B and then, by interpolation, calculates the P_I value of any other mixture as desired.

The key mixtures are conceived of being made (as opposed to actually being made) of equal parts (pt) of appropriate components according to the sequence in table 2.

Table 2. Design for preparing key mixtures of sediments A and B to enable calculation of P redistribution among sediments from different source areas

Key mixture[1]	Equation for preparing mixture	Key mixture is product of equation(s)--
A:B	1. 1 pt A + 1 pt B = 2 pt A:B	1
3A:B	2. 2 pt A:B + 2 pt A = 4 pt 3A:B	1+2
A:3B	3. 2 pt A:B + 2 pt B = 4 pt A:3B	1+3
A:7B	4. 4 pt A:3B + 4 pt B = 8 pt A:7B	1+3+4
A:15B	5. 8 pt A:7B + 8 pt B = 16 pt A:15B,	1+3+4+5

[1]The ratio symbol indicates the proportion of A and B in each mixture.

We selected 3A:B and A:15B to represent the maximum A and B contents because our experience with the soil type showed that the sorption isotherm of each of these two mixtures did not differ appreciably from that of its major component.

The computer calculates the P_I values of the above five mixtures in the same sequence that the mixtures are "made." Because each mixture consists of equal parts of two components, its P_I value is based on a simple average of the P_I values of its two componets. P_I values of mixtures with A:B ratios between those of the above mixtures are calculated by a simple average weighting procedure. Finally, the computer calculates EPC by using the controlling equation. If desired, isotherms can be drawn through the P_I and EPC values.

We devised a model which was consistent with experimental data from seven different mixtures of Lo-P and Hi-P Mahantango soil, (namely, A, B, and their key mixtures). We found that when 55 percent was used as the P fixation coefficient, the calculated and experimentally determined EPC's were nearly identical. If modeling efforts similar to ours are attempted and if the controlling equation and P fixation coefficient were not known, consideration might be given to obtaining both these pieces of information experimentally from the sorption isotherms of the above-mentioned seven types of soil samples. The equation and fixation coefficient would then be based on sufficient data, and the comparison of the calculated and experimentally determined isotherms would be readily accomplished.

CONCLUSIONS

We have developed a model for describing the P sorption characteristics of two-soil mixtures representing all the ratios in which the same two component soils can be combined. The resultant of mixtures of three (or more) sediments can be resolved by combining the first two sediments, then combining that resultant with the third sediment and so forth. The model can therefore be used to characterize the transport of P in watersheds via streams that carry significant amounts of P in both liquid and solid phases and that change continually in the P sorption characteristics of the solid phase. The model is flexible, being applicable to all or selected areas within a watershed. Because of this flexibility, it can be used to provide information that would enable managers of land and water resources to tailor practices for reducing P losses and P pollution of streams according to specific areas within watersheds.

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SOIL AND WATER FACTORS AFFECTING EPC

Robert C. Wendt[1]

INTRODUCTION

Equilibrium phosphate concentrations (EPC's) have been used extensively as a means of assessing the pollution potential of soils and sediments (Taylor and Kunishi 1971, McDowell and McGregor 1980). Several factors, including the period of equilibration, amount of P adsorbed, solution-to-soil ratio, vigor of mixing, microbial activity, type and amount of electrolyte in the equilibrating solution, and extent of particle aggregation, may influence P adsorption-desorption reactions and, thus, values of EPC obtained. Effects of these factors may be largely eliminated from relative comparisons by standardizing measurement conditions. However, if results of EPC determinations are to be used to predict behavior of P on sediments in runoff, effects of several of the above factors may need to be accounted for either by selecting measurement conditions expected to approximate those in runoff or, if factors vary widely in runoff, by adding additional model parameters to account for their effects. This report will briefly discuss the influence of each of the above factors.

PERIOD OF EQUILIBRATION

The EPC has been shown to be relatively insensitive to the period of equilibration (Taylor and Kunishi 1971). However, slopes of isotherm segments, such as that illustrated in figure 1, tend to increase with equilibration time, pivoting approximately on the EPC as adsorption and desorption reactions continue (Taylor and Kunishi 1971). Hence, the slopes, termed "P buffer capacities," will depend on the equilibration time used.

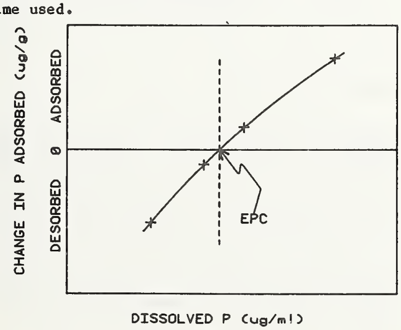

Figure 1.--Typical segment of P adsorption-desorption isotherm from which the EPC is estimated by extrapolation.

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Rates of adsorption and desorption are initially rapid followed by a period of slower reaction rates. The more rapid reactions usually reach completeness within a few minutes or hours (Barrow and Shaw 1975a), but slower reactions may continue for days or months (Enfield and Bledsoe 1975). Most runoff events are expected to occur over a period of a few hours or less and, thus, the fast reactions will dominate P adsorption and desorption reactions on soil particles in runoff in most cases. Use of equilibration times of sufficient length to encompass the majority of fast reactions will provide estimates of the maximum expected P buffer capacity. Such estimates should be applicable to sediments in runoff as a steady state between dissolved and adsorbed P forms is approached. Although selection of an appropriate equilibration time may be somewhat arbitrary, buffer capacities consistent with observed amounts of P desorbed have been obtained using a 6-hr time period (Taylor and Kunishi 1971).

TEMPERATURE

In describing effects of temperature on P reactions in soils, it is convenient to divide P into three forms (Barrow 1979)

$$\text{dissolved P} \rightleftarrows \text{adsorbed P} \rightleftarrows \text{firmly held P}$$

Phosphate dissolved in solution is assumed to equilibrate with adsorbed P. Firmly held P is assumed to equilibrate with adsorbed P, but not directly with P in solution. The distribution of solid-phase P between adsorbed and firmly held forms is based primarily on kinetic considerations. Thus, quantities of P in the adsorbed and firmly held categories are somewhat analogous to quantities associated with fast and slow reactions, respectively.

Although varying temperature does not greatly affect the relative distribution of P between adsorbed and firmly held forms, increasing temperature causes a shift to dissolved forms (Barrow 1979), indicating that the adsorption process is exothermic. EPC determinations are usually made using short equilibration times; hence, dissolved and adsorbed P are the primary forms involved. Thus, increasing the temperature of measurement should increase the EPC and probably reduce the slope of the isotherm segment used for estimating buffer capacity. An approximately twofold increase in EPC determined at 25° C compared with that determined at 10° C has been observed (Barrow and Shaw 1975a). Similar effects would be expected with temperature variations in runoff. However, sufficient data are not available to estimate the magnitude of these effects over a variety of soil types.

AMOUNT OF P ADSORBED

Adsorption isotherms relating the change in P adsorbed per unit mass of solid to dissolved P levels in solution may be approximately linear over short segments such as those used for determining EPC (Taylor and Kunishi 1971). Over wide ranges of dissolved and adsorbed P, however, adsorption isotherms are typically curved, having positive slopes that decrease with increasing amounts of P adsorbed. Hence, slopes of isotherm segments are expected to decrease with increasing EPC for a given soil (fig. 2). As a result, the usefulness of buffer capacity estimates for predicting the distribution of P between dissolved and adsorbed forms may diminish as dissolved P concentrations exceed the range used for EPC measurement.

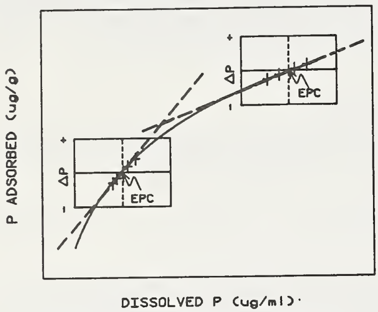

Figure 2.--P adsorption isotherm illustrating changes in P buffer capacity with EPC.

Errors resulting from extrapolations outside the range of measurement may be partially overcome by using nonlinear adsorption models to describe the relationship between dissolved and adsorbed P forms. However, this would increase the number of parameters needed to describe P adsorption, some of which would not be easily obtained. Moreover, the nonlinear adsorption models may also fail to fully describe P adsorption over wide concentration ranges (Barrow 1978). Thus, some extrapolation error would still be expected. However, these errors, although substantial, may be relatively small compared to those introduced in the hydrologic and sediment transport models or by assumptions on spatial variability.

HYSTERESIS

Phosphate adsorption isotherms have often been observed to exhibit hysteresis in which less P is desorbed for equivalent changes in dissolved P than is adsorbed (fig. 3) (Barrow and Shaw 1975b, Fox and Kamprath 1970). Hysteresis is thought to be caused by the continued slow conversion of adsorbed P to more firmly held forms. When sufficient time for P desorption is allowed (Madrid and Posner 1979) or when equilibration times are sufficiently short for slow reactions to be negligible (White and Taylor 1977), P adsorption reactions appear to be essentially reversible. EPC measurements primarily involve the fast reactions and, in the case of runoff, are applied to a system in which slow reactions are expected to have a minor effect. Hence, for this application, the assumption of isotherm reversibility should not result in major errors. However, an exception may be when major disequilibrium conditions exist (within sample heterogeniety with respect to P) in soil due to recent fertilizer P additions or severe depletion of P from localized areas by plant roots.

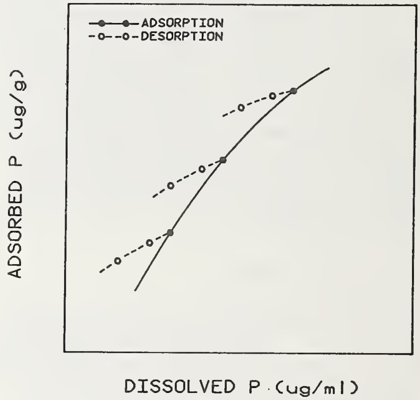

Figure 3.--P adsorption isotherm showing hysteresis frequently observed with subsequent P desorption.

SOLUTION-TO-SOIL RATIO

Experimentally determined phosphate adsorption isotherms have been shown to vary with the ratio of water to soil or sediment, often termed the "solution-to-soil ratio" (Barrow and Shaw 1979, Hope and Syers 1976). Hence, relationships between concentrations of dissolved and adsorbed P determined at standard solution-to-soil ratios may often be in error when applied to sediments in runoff over a range of sediment concentrations. The influence of the solution-to-soil ratio on P adsorption is thought to be due to breakup of aggregated soil particles during shaking (Barrow and Shaw 1979). At lower solution-to-soil ratios, aggregates are postulated to break up more rapidly. This exposes additional sites for P adsorption, resulting in greater amounts of P adsorbed. The magnitude of the effect varies with vigor of shaking and soil type, presumably due to differences in aggregate stability among soils.

For application of results of adsorption studies to field soils, Barrow and Shaw (1979) have recommended that equilibration procedures which minimize particle breakdown be used for soils with aggregates of low stability. Soil particles in runoff, however, have experienced some dispersive forces during detachment and entrainment. Thus, special precautions to minimize breakdown during equilibration may not be appropriate. But because the magnitude of dispersive forces is expected to vary with event, it is not possible to recommend a single solution-to-soil ratio or method of agitation that would be directly applicable in all cases.

MICROBIAL ACTIVITY

Little effect of microbial activity on soil P is expected over equilibration times of a few hours or less. Thus, EPC determinations using such equilibration times should not be greatly influenced by microbial activity.

TYPE AND AMOUNT OF ELECTROLYTE

Increasing the concentration of neutral salt in aqueous, supporting solutions shifts the distribution of dissolved and adsorbed P in favor of the latter (Barrow 1972, Clark and Peach 1960). Thus, the choice of the amount and type of electrolyte in equilibrating solutions will influence the results of EPC determinations. Many studies of P adsorption on soil have been performed using an equilibrating solution of 0.01 $\underline{M}$ $CaCl_2$. Calcium is the predominant cation in many agricultural soils; and, for many soils, this solution is a reasonable approximation of the Ca concentration in soil solution (Olsen and Khasawneh 1980). Thus, it may be useful when P concentrations in equilibrating solutions are to be used for estimating dissolved P levels in soil solution or for comparing intrinsic differences among soil and sediment samples. However, lower Ca concentrations are expected in runoff water due to dilution. Moss (1963) observed Ca concentrations in soil water to decrease rapidly with dilution up to solution-to-soil ratios of approximately 1 to 1 and to decline less rapidly with further dilution. At solution-to-soil ratios of 100 to 1, Ca concentrations were about one-twentieth that at 0.4 to 1. Thus, for direct application of results to runoff, a dilute electrolyte solution such as 0.01 $\underline{M}$ $CaCl_2$ will probably be excessive in most instances. Equilibrations in water at sufficiently wide solution-to-soil ratios to avoid the region where Ca concentrations change rapidly with dilution may be more appropriate.

DISCRETE PARTICLE SIZE AND AGGREGATION

Because of greater surface area per unit mass, smaller-sized, discrete soil particles should contain greater quantities of adsorbed P and sites for P adsorption. Hence, their mass should contribute disproportionately more to the solution P buffer capacity than that of larger particles. However, aggregation of smaller, discrete particles may influence amounts of adsorbed P and the P buffer capacity by reducing reaction rates with internal particles (Evans and Syers 1971, Alberts et al. 1983).

Because smaller-sized particles tend to be eroded preferentially (Stoltenberg and White 1953) and exhibit greater concentrations of adsorbed P, the size distributions of aggregated and dispersed particles in soil and suspended sediment loads are important considerations for predicting P movement in runoff. Preferential removal of small particles results in sediments having both greater adsorbed P concentrations at equivalent dissolved P levels and greater P buffer capacities than those indicated from EPC determinations on the source soil. It may be possible to obtain appropriate correction factors, termed "enrichment ratios," from relatively simple functions of sediment concentration as is done for total P (Menzel 1980). However, because much sediment in runoff may be in the form of water stable aggregates (Alberts and Moldenhauer 1981), predicted enrichment based on changes in the proportion of discrete particles may result in overestimation where aggregation significantly restricts reaction rates on some particles.

OVERVIEW

If EPC determinations are used for making comparisons of P status among samples or as input to empirical predictive models, the above factors should not be critical. For the former application, standardizing the data collection procedures for all samples will eliminate most effects. For the latter, on-site calibration of the model can compensate for these differences. If the user's objective is to describe P reactions in runoff, the conditions of measurement affecting P reactions should approximate those expected in runoff as closely as possible. Although many of these conditions may be roughly approximated, unaccounted for variations in each in runoff are likely to contribute to prediction errors.

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THE ROLE OF DESORPTION KINETICS IN MODELING THE TRANSPORT OF PHOSPHORUS AND RELATED ADSORBED CHEMICALS IN RUNOFF

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INTRODUCTION

Due to the high cost and long time needed to obtain reliable data on nutrient and pesticide losses in runoff, increasing efforts are being made to model the processes associated with their transport in runoff, in conjunction with existing models for hydrologic and sediment loss (Donigian et al. 1977, Williams and Haan 1978 Frere et al. 1980, Leondard and Wauchope 1980). Two recently developed models, which include phosphorus (P) and pesticides are the ARM (Agricultural Runoff Management) model (Donigian et al. 1977) and the CREAMS (Chemicals Runoff, and Erosion from Agricultural Management Systems) model (Knisel 1980). Both these models are physically based descriptions of the processes involved in chemical transport, assuming first-order kinetics and equilibrium conditions, respectively, to operate between the adsorbed and solution P forms in soil. Limited field testing of the ARM and CREAMS models, however, has shown that the prediction of both adsorbed and solution phase chemicals is not satisfactory (Donigian et al. 1977, Davis and Donigian 1979, Frere et al. 1980, Leondard and Wauchope 1980).

A simplified kinetic model describing the desorption of soil P has been recently developed (Sharpley et al. 1981b):

$$P_d = K\,P_o\,t^{\alpha}\,W^{\beta} \qquad (1)$$

where P_d is the amount of soil P desorbed (μg P/g soil) in time t (min) at a water:soil ratio (cm^3/g soil) W, P_o the initial amount (μg P/g soil) of desorbable or available P present in the soil, and K, α, and β are constants for a given soil.

The model equation 1 was subsequently developed to describe the transport of soluble P in runoff from soil boxes under simulated rainfall of constant rate (Sharpley et al. 1981a) where steady runoff began very shortly after the start of rainfall:

$$P_R = \frac{K\,P_o\,S\,t^{\alpha}\,W^{\beta}}{V} \qquad (2)$$

where P_R is the storm average soluble P concentration of runoff (μg P/L), t the storm duration, S the mass of soil in the interacting zone (g), and V the total rainfall during an event (cm). The mass of soil in the interacting zone is calculated as EDI * BD, where EDI is the effective depth of interaction between surface soil and runoff in the transport of soluble P (cm), and BD is the bulk density of soil (g/cm).

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Although EDI has been shown to depend upon the kinetic energy of raindrop impact on soil surface, soil slope, slope length, soil surface shaping, and presence of clods at the soil surface (Sharpley et al. 1981a, Ahuja et al. 1982, Ahuja et al. 1983), a constant value of EDI is used for each watershed.

At the moment, application of equation 1 is restrictive, due to the fact that the constants have to be determined for a given soil prior to their use. The following experimental analysis, therefore, investigates the relationships between equation constants and soil properties for 60 soils (0-10 cm depth) from throughout the continental United States and discusses their application to modeling soluble P losses in runoff from agricultural watersheds. The location, soil taxonomy, and physical and chemical properties of the soils have been presented by Sharpley et al. (1982).

RESULTS AND DISCUSSION

Model Constants

The constants of equation 1 were highly correlated with the ratio of clay:organic C content for all soils (figure 1).

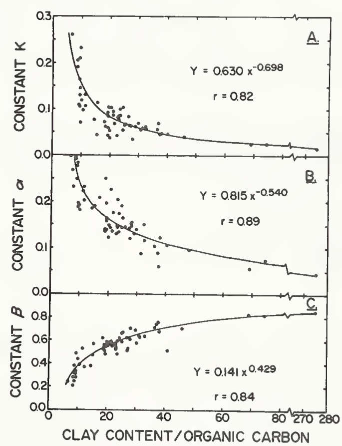

Figure 1--Relationship between the constants of equation 1 and the ratio of clay/organic carbon content of the 60 soils and ash.

The ratio of clay:organic C content is used in this case to represent the interactive surface of a soil involved in P adsorption and desorption. In this respect, the most interactive soil surfaces are those of sesquioxide or mineral nature (Larsen and Widdowson, 1970, Sharpley et al. 1982a) and those of organic matter least interactive (Dalton et al. 1982, Moshi et al. 1974, Singh and Jones, 1976).

For general field application of equation 2 the constants K, α, and β for a given soil can be calculated from percent clay:organic C content using the following relationships:

$$K = 0.630 \text{ (percent clay:organic C)}^{-0.698} \quad (3)$$

$$\alpha = 0.815 \text{ (percent clay:organic C)}^{-0.540} \quad (4)$$

$$\beta = 0.141 \text{ (percent clay:organic C)}^{0.429} \quad (5)$$

Field Application of the Kinetic Model

Phosphorus

The soluble P concentration of runoff from several Southern Plains watersheds was predicted using equation 2. Detailed descriptions of the watersheds discussed are given by Sharpley et al. (1982b), and the parameters of equation 2 for each major soil type at each watershed location are presented in table 1.

Table 1.--Parameters used in the kinetic equation (2) to predict soluble P concentration of runoff from the watersheds

Location and soil type	Kinetic constants K	α	β	EDI	Bulk density
				mm	g/cm
El Reno, OK Kirkland loam	0.172	0.299	0.313	0.30	1.40
Riesel, TX Houston Black clay	0.071	0.150	0.541	0.30	1.35
Woodward, OK Woodward loam	0.057	0.127	0.619	0.30	1.40

Values of the constants K, α, and β were calculated from the percent clay:organic carbon content, using equation 3, 4, and 5, respectively. Storm duration, t, was set at 30 min, an approximate value for an average storm size. Actual storm duration data were not available. The effective depths of interaction used in the present testing were those measured with simulated rainfall (6 cm/hr) and a fine screen covering the soil to simulated vegetative cover (Sharpley et al. 1981a). Bulk densities were obtained from field measurement. Annual runoff volume and available P (Bray-1) content of surface soil (0-1 cm depth) from the watersheds were used. Available P content was measured in March each year.

Soluble P prediction was good over a wide range of concentrations (30-500 µg/L), fertilizer and management practices, soil types and vegetative covers (table 2 and figure 2). Predicted concentrations at the El Reno, Bushland, and

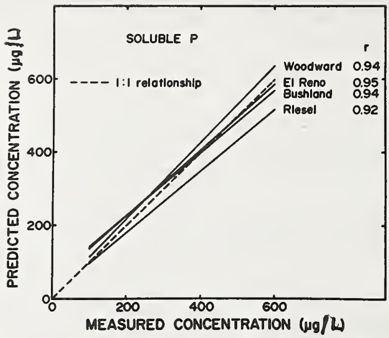

Figure 2--Relationship between measured and predicted (using equation 2) mean annual, soluble P concentration of runoff. All relationships are significant at 95% level.

Woodward watersheds, however, were slightly higher than measured values. In contrast, predicted concentrations for the Riesel watersheds were generally lower than measured values. In the present testing, only one estimate of available P was used each year, due to a lack of field data. The available P content of the surface soil will change during a growing season with fertilizer P addition, plant wash-off and decay, organic P mineralization, immobilization, and plant uptake. It is expected, therefore, that more frequent measurements of available P or the interfacing of SWAM with models simulating soil P cycling such as EPIC (Williams et al. 1983), will improve the prediction of soluble P concentration in runoff.

Observed discrepancies between measured and predicted values may also result from the fact that contributions from plant and residue wash-off to soluble P transport in runoff (McDowell et al. 1980, Sharpley 1981) are not included in the present testing.

As runoff and not rainfall volume was used in equation 2 and only a portion of the incident rainfall leaves a watershed as runoff, predicted soluble P concentrations will be smaller than those shown in table 2 if rainfall volume had been used in equation 2. In addition, effective depth of interaction between surface soil and runoff was constant for each watershed location in the present analysis. As model application becomes more refined, changes in effective depth of interaction with rainfall and management characteristics may improve the predictions.

Table 2--Measured and predicted mean annual flow-weighted soluble P concentration of runoff from the watersheds using kinetic equation 2.

Watershed	Location	1977 Meas.	1977 Pred.	1978 Meas.	1978 Pred.	1979 Meas.	1979 Pred.	1980 Meas.	1980 Pred.
		µg/L							
FR-1	El Reno,	170	187	145	139	100	125	129	171
FR-2	OK	68	99	104	145	80	135	348	311
FR-3		70	70	80	111	100	123	84	119
FR-4		117	125	104	137	320	336	472	501
FR-5		147	140	104	174	410	405	72	263
FR-6		--	--	203	216	290	331	163	188
FR-7		179	208	211	297	490	506	137	190
FR-8		168	191	181	217	280	286	83	114
G-10	Bushland,	--	--	93	104	171	210	115	138
G-11	TX	--	--	152	171	207	216	420	433
G-12		--	--	148	171	--	--	72	195
W-1	Woodward,	163	212	173	170	170	186	179	184
W-2	OK	95	130	116	121	120	130	140	177
W-3		100	122	100	117	100	97	197	217
W-4		109	138	92	96	90	96	194	213
Y	Riesel,	120	118	90	91	100	85	132	117
Y-2	TX	150	148	90	93	80	73	137	136
Y-6		50	54	70	90	50	45	61	68
Y-8		60	67	50	62	30	32	99	122
Y-10		--	--	30	42	50	41	86	104
Y-14		60	45	60	62	110	68	42	54
W-10		112	102	130	115	80	80	62	60
SW-11		70	80	70	77	30	45	112	108

Pesticides

As was the case for P, a lack of experimental studies relating the kinetics of desorption in the laboratory with the release of several pesticides to runoff, precludes model testing. The applicability of the kinetic equation to modeling pesticide release to runoff has been recently discussed by Ahuja et al. (1982b). Using data of Baker et al. (1979) on the movement of alachlor, atrazine, and propachlor pesticides in runoff from field plots under simulated rainfall, Ahuja et al. (1982b) observed that a log-log plot of pesticide concentration and time was linear. This data along with a similar treatment of 2,4-D losses in runoff (White et al. 1976) are presented in figure 3. The linear form of the log-log plot is the same as that observed for P (Sharpley et al. 1981a) and is in agreement with the kinetic equation. This is in contracst to a semi-log plot of pesticide concentration in runoff as a function of time, which showed a definite curvature (White et al. 1976, Ahuja et al. 1982b). The data suggest, therefore, that the kinetic equation may be applicable to pesticide transport in runoff.

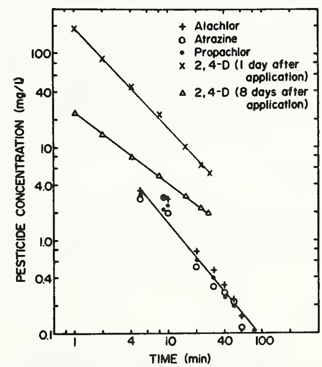

Figure 3--Log-log plot of pesticide concentrationin runoff as a function of time during a rainfall event, as a test of the kinetic equation. Alachlor, atrazine, and propachlor are from Baker et al. (1979), and 2,4-D from White et al. (1976).

FURTHER RESEARCH

Further research is needed in the following areas to improve model application and prediction:

1. The application of the kinetic equation to pesticide desorption should be evaluated with laboratory batch experiments, as used for P. It is hoped that the parameters K, α, and β will be constant for a given soil and pesticide. Several pesticides must be evaluated due to the great variation in pesticide chemistry.

2. The kinetic approach may also be applicable to describing processes occurring after the adsorbed chemical leaves the edge of the field. As reaction time between river or lake sediment and overlying water will be longer than that for surface soil and runoff, equilibrium relationships may be more appropriate. Comparative research is needed, however, to establish which procedure should be used.

3. For application of the kinetic equation to a field situation, input data (runoff volume) and parameters (K, α, and β) may be predicted from hydrologic models and soil properties, respectively. Since frequent estimates of of available P are needed, models simulating the soil P cycle should be developed and interfaced with SWAM.

4. As plant and residue washoff can contribute soluble P to runoff, the kinetic equation must be interfaced with relationships estimating these contributions.

5. Sufficient field data must be obtained from watersheds, to apply the kinetic equation on a storm to storm basis and compared with measured values. These data must be obtained from a wide area of the country, covering different soil types and land management practices.

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ESTIMATION OF PHOSPHORUS MODEL PARAMETERS FROM LIMITED SOIL SURVEY INFORMATION

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INTRODUCTION

The simplified soil and plant phosphorus (P) model incorporated into EPIC (Jones et al. 1983) is designed to use soil chemical, physical, and taxonomic data available in U.S. Soil Conservation Service (SCS)/State Agricultural Experiment Station Soil Survey Investigative Reports (SSIR) and SCS soil pedon descriptions. Three soil parameters -- labile P content (P_{il}, represented here by extraction with anion exchange resin), organic P content (P_o), and an index of fertilizer availability (F_a) -- are not normally included in these reports and descriptions. Therefore, P_{il}, P_o, and F_a must be estimated from more readily available data on extractable soil P (Bray 1 P, BP; Olsen P, OP, and Mehlich P, MP) and soil chemical, physical, and taxonomic information included in SSIR's and SCS soil pedon descriptions.

This paper presents regression equations to estimate P_{il}, P_o, and F_a from data available in SSIR and SCS pedon descriptions. The equations are derived from regression analysis of 92 soils from the continental United States and Puerto Rico.

MATERIALS AND METHODS

Surface samples (0-10 cm depth) and supporting laboratory and taxonomic data for 92 soils from the continental United States and Puerto Rico were obtained from the SCS National Soil Survey Laboratory. Soils were chosen on the basis of their agricultural importance, availability of soil samples, and availability of adequate laboratory data for the samples.

Anion exchange resin P was determined by adding 5 cm^3 IRA-400 anion exchange resin (bicarbonate form) to 4 g soil in 40 mL distilled water. The sample was shaken on an oscillating shaker at 180 oscillations/min for 16 h. A 60-mesh screen was used to separate soil from resin. Phosphorus was removed from the resin with 100 mL 1.5 M NaCl for 24 h with occasional stirring. Bray P, OP, and MP were determined by the methods of Bray and Kurtz (1945), Olsen et al. (1954), and Sabbe and Breland (1974), respectively. Organic P content was determined as the difference between P extracted from ignited (550°C) and nonignited soil samples with 1 M H_2SO_4 (Walker and Adams 1958). Fertilizer availability (F_a) was estimated by adding 0, 60, 120, 240, and 480 g P (as a solution of KH_2PO_4) to 4 g subsamples of soil in small plastic vials. Soil was brought to field capacity with distilled water and air-dried in the laboratory. The soil was rewet and allowed to air-dry twice more during a 6-month period before extraction with anion exchange resin. The relationship between P_{il} and P added was determined by linear regression analysis and F_a is the slope of that relationship for each soil.

RESULTS AND DISCUSSION

Preliminary analysis indicated that errors in the estimation of P_{il} and F_a were smaller when the soils were divided into groups based on the presence of $CaCO_3$ and degree of weathering. The following groups were defined: calcareous soils -- soil with free $CaCO_3$; highly weathered soils -- Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols, and acidic Ochrepts; and slightly weathered soils -- all other soils (mostly Mollisols).

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Table 1.--Median, mean, and range of several properties of three groups of soils used in this study

Soil Group	pH	Clay	$CaCO_3$	Organic C	CEC	F_a	Organic P	P test: Labile	Bray	Mehlich	Olsen
		%	%	%	meq $100g^{-1}$		$\mu gP\ g^{-1}$	$\mu gP\ g^{-1}$	$\mu gP\ g^{-1}$	$\mu gP\ g^{-1}$	$\mu gP\ g^{-1}$
Calcareous (20 soils)											
Median	7.7	23	0.8	1.4	17	0.51	166	17	11	34	9
Mean	7.7	24	9.1	1.4	20	0.53	147	13	20	67	13
Minimum	7.1	10	0.5	0.4	8	0.19	33	6	1	3	3
Maximum	8.4	67	54.0	3.2	55	0.66	403	56	77	338	38
Slightly Weathered (35 soils)											
Median	6.3	22	--	1.7	16	0.48	218	19	21	36	12
Mean	6.4	22	--	1.7	17	0.49	193	16	24	53	13
Minimum	5.2	6	--	0.2	5	0.07	37	4	4	3	3
Maximum	8.3	62	--	3.5	43	0.74	442	53	79	215	42
Highly Weathered (23 soils)											
Median	5.6	10	--	1.4	8	0.26	231	13	47	42	19
Mean	5.6	15	--	1.6	8	0.25	182	11	66	43	20
Minimum	4.4	1	--	0.4	1	0.06	29	3	3	2	2
Maximum	6.8	76	--	3.8	21	0.51	656	43	222	147	50

The ranges and means of several chemical and physical properties of the soils are given in table 1. Equations presented in this paper should not be used with soils data outside the ranges in table 1.

Labile Phosphorus

Labile P was linearly related to the amount of P extracted by the Bray, Olsen, and Mehlich techniques (table 2).

Table 2.--Relationship between labile P (P_{il}) and Olsen P (OP), Bray P (BP), and Mehlich P (MP)

Equation	Root mean square error	R^2
Calcareous (n=20)		
P_{il} = 0.55 BP + 6.1	6.1	0.83
= 1.09 OP + 3.2	6.5	0.74
= 0.10 MP + 10.2	9.0	0.51
Slightly Weathered (n=35)		
P_{il} = 0.56 BP + 5.1	5.2	0.79
= 1.07 OP + 4.1	5.4	0.77
= 0.13 MP + 11.4	8.8	0.39
Highly Weathered (n=23)		
P_{il} = 0.14 BP + 4.2	4.7	0.76
= 0.55 OP + 2.1	6.1	0.61
= 0.24 MP + 2.9	3.9	0.84

In most cases, more than 70 percent of the variation in P_{il} was explained by the regression equations. The relationships given in table 2 were tested using data presented by Enwezor (1977), Maida (1978), and Rudd and French (1976) (figure 1).

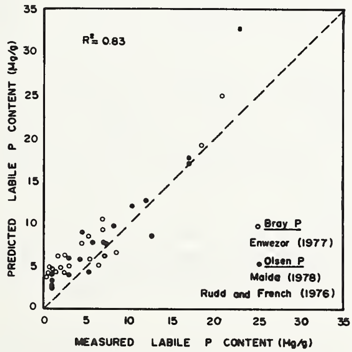

Figure 1.--Relationship between measured and predicted labile P using equations in table 2 and Bray and Olsen P.

In these studies both P_{il} (resin extractable) and BP or OP were determined in the same soils from southeastern Nigeria, Malawi, and South Australia, respectively. A close agreement between measured P_{il} and that predicted from BP or OP was obtained.

Organic Phosphorus

The P_o content of soils in this study was linearly related to total N (N_t) (figure 2).

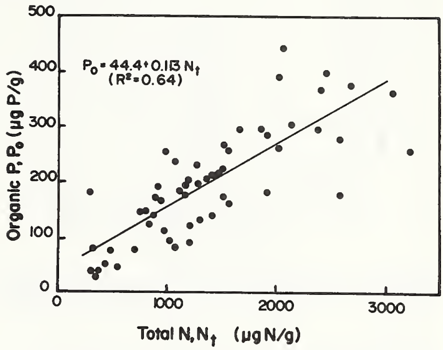

Figure 2.--Relationship between total nitrogen and organic P.

These results are consistent with previous studies (Greb and Olsen 1967, Thompson et al. 1954, Walker and Adams 1958). The relationship presented in figure 2 for the surface soils of this study was tested using data presented by Grunes et al. (1955) and Sharpley et al. (1982). A close agreement between measured P_o and that predicted from N_t was found (figure 3).

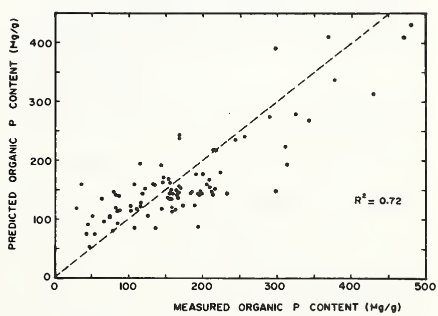

Figure 3.--Relationship between measured organic P and that predicted from total nitrogen.

Fertilizer Phosphorus Availability

Fertilizer availability was measured as the slope of the linear relationship between labile P and amount of P added, and examples of this relationship are given in figure 4. Regression

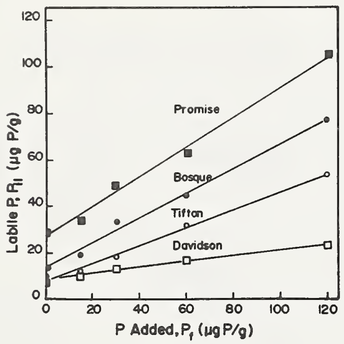

Figure 4.--Relationship between amount of P added and labile P content after a 1 month incubation.

analysis was used to relate F_a to soil data available in SSIR and SCS pedon descriptions (table 3). Fertilizer P availability increased with a decrease in $CaCO_3$ and clay content for the calcareous and highly weathered soils, respectively. For the slightly weathered soils, an increase in labile P, base saturation, and pH was associated with an increase in F_a. These results are consistent with those of previous studies which have shown that in calcareous soils

Table 4.--Equations for estimation of fertilizer P avialability index (F_1) from $CaCO_3$, labile P (P_{i1}), base saturation (BS), pH (PH), clay (CL), and organic carbon (OC)

Equation	Root mean square error	R^2
Calcareous (n=20)		
$F_1 = -0.0061\ CaCO_3 + 0.58$	0.069	0.71
Slightly weathered (n=35)		
$F_1 = 0.0043\ BS + 0.0034\ P_{i1} + 0.11\ PH - 0.70$	0.098	0.75
Highly weathered (n=23)		
$F_1 = -0.047\ \text{Ln}\ CL + 0.0045\ P_{i1} - 0.053\ OC + 0.39$	0.070	0.78

P sorption increases with increasing $CaCO_3$ content (Larsen and Widdowson 1970, Williams et al. 1971) and that P sorption is reduced by previous additions of fertilizer P (Barrow 1974). In addition, P sorption has been shown to be positively correlated with clay content (Juo and Fox 1977, McCallister and Logan 1977, Syers et al. 1971) and negatively correlated with base saturation (Brown and Loewenstein 1978). Due to a lack of published data the relationships used to predict F_a could not be tested.

SUMMARY

This paper presents equations which can be used to initialize labile P, organic P, and fertilizer P availability index for the simplified soil P model used in EPIC (Jones et al. 1983). Labile P , Bray P, Olsen P, and Mehlich P were measured. Relationships between extractable P and labile P were determined for the following soil groups: calcareous, slightly, and highly weathered. For each group, at least two of the three extractants accounted for over 70 percent of the variation in labile P. Organic P was found to be a linear function of soil N. Fertilizer P availability index was related to $CaCO_3$, clay, and labile P content and base saturation.

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SOIL TEST P MEASUREMENTS FOR PREDICTING LABILE P AND EPC ON NONCALCAREOUS AGRICULTURAL SOILS[1]

Ann M. Wolf, Dale E. Baker, Harry B. Pionke, and Harry M. Kunishi[2]

INTRODUCTION

The use of models both for predicting uptake of phosphorus (P) by plants and for estimating the loss of P from agricultural land has become quite common. It is important that users of these models have reliable values for the biologically available P in soils. The soil fractions of P considered most important for predicting biologically available P are (1) the P in the soil solution and (2) labile P or that quantity of soil P in rapid equilibrium with solution P (Larsen 1967).

Labile P has traditionally been determined using isotopic dilution techniques where P^{32} is added to a soil and its distribution between the solid and solution phases is determined after a period of equilibration (Russell et al. 1954). Alternative approaches are to use adsorption/desorption isotherms to estimate the labile P in soils (Kunishi and Taylor 1977) or to use an anion saturated exchange resin to extract soil P (Amer et al. 1955). Soil solution P may be determined by measuring water-soluble P or from adsorption/desorption isotherms to determine the equilibrium phosphorus concentration (EPC) at zero P adsorption (Kunishi and Taylor 1977).

Because of the cost and time involved in performing the above analyses, quick tests for P, such as Olsen's $NaHCO_3$ (Olsen et al. 1954), Bray I (Bray and Kurtz 1945), and Mehlich I (Sabbe and Breland 1974) have been developed. These tests are used widely as a means of estimating plant available P in soils, and their success depends on correlation and calibration studies that must be performed to establish the relationship between plant growth or plant uptake of P and the P extracted by the soil test. Because of the ease with which these tests can be performed, at least one group of researchers (McDowell et al. 1980) has proposed that these tests be used to estimate labile P and solution P in soils and to generate input for P models.

The primary objective of this study was to evaluate how well labile P and the equilibrium phosphorus concentration (EPC) could be estimated from the Olsen, Bray I, and Mehlich I soil test values on a diverse group of noncalcareous agricultural soils. Because several different procedures are currently used to measure labile P in soils, a secondary objective was to evaluate the relationships among labile P measurements determined by isotopic exchange, by resin extraction, and from the intercept of adsorption/desorption isotherms.

MATERIALS AND METHODS

Soils

The soils used in this study were noncalcareous agricultural soils collected from sites in different regions of the United States where P fertility experiments were being performed or had been performed in the past by different State universities. The soil types and States from which the soils were collected are presented in table 1.

As part of the fertility experiments, each of the soil types collected had been treated with several rates of fertilizer P. The number of rates applied varied with the individual experiment and are shown in table 1. At each site a soil sample was collected from each fertilizer treatment so that samples with a range of P contents were available for each soil type. A total of 87 soil samples were collected and used in this study to evaluate the relationships of labile P and EPC to soil test P measurements.

The textures of the soils ranged from loamy sand to silty clay loam (table 1). The soils were from the Ultisol, Alfisol, and Mollisol orders. While these three orders represent only a few of those present in the United States, they are present on over 80 percent of the total land area of the States from which the soils were collected (Buol 1973, Krusekopf 1960, Miller and Quandt 1984).

The soils were separated into the three regional groups shown in table 1 on the basis of the soil test for P most commonly performed in the State from which the soil was collected and because of differences that exist among soils which have developed in different regions of the country. The most commonly performed test for P in the North Central Region is Bray I, although Olsen's $NaHCO_3$ is used by some of the laboratories as well. Most of the soils in this region developed from loess parent materials, under grassland vegetation, in an area characteristically having a seasonal moisture deficit. The soil test most commonly used in the Southeast Region is Mehlich I. All of the soils collected from this region were Ultisols. The last group of soils were from Pennsylvania and Ohio. Many of the soils in these two States developed under forest vegetation and under similar climatic conditions. The most commonly used soil test for P in both Pennsylvania and Ohio is Bray I.

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Table 1. Soils used in study

State from which soil was collected	Soil type	Number of P fertilizer treatments	Soil order
---------- North Central Soils ----------			
Illinois	Cisne silt loam	5	Alfisol
Missouri	Creldun silt loam	3	Alfisol
Illinois	Flanagan silt loam (corn plot)	3	Mollisol
Illinois	Flanagan silt loam (soybean plot)	3	Mollisol
Nebraska	Hastings silt loam	3	Mollisol
Wisconsin	Plano silt loam	3	Mollisol
Indiana	Raub silt loam	3	Mollisol
Nebraska	Sharpsburg silty clay loam	3	Mollisol
Iowa	Webster clay loam	3	Mollisol
Minnesota	Webster clay loam	3	Mollisol
Missouri	Winfield silt loam	3	Alfisol
Kansas	Woodson silt loam	3	Mollisol
---------- Southeastern Soils ----------			
Alabama	Benndale loamy sand	5	Ultisol
Georgia	Cecil sandy clay loam	5	Ultisol
Tennessee	Dickson silt loam	4	Ultisol
New Jersey	Freehold sandy loam	2	Ultisol
Alabama	Hartsells fine sandy loam	5	Ultisol
Maryland	Mattapex silt loam	3	Ultisol
South Carolina	Pacolet silty clay loam	2	Ultisol
North Carolina	Portsmouth fine sandy loam	3	Ultisol
Florida	Red Bay fine sandy loam	3	Ultisol
Virginia	Tatum silt loam	5	Ultisol
---------- Pennsylvania and Ohio Soils ----------			
Pennsylvania	Hagerstown silt loam (no-till)	3	Alfisol
Pennsylvania	Hagerstown silt loam (conventional till)	3	Alfisol
Ohio	Wooster silt loam (corn plot)	3	Alfisol
Ohio	Wooster silt loam (soybean plot)	3	Alfisol

Labile P and EPC Measurements

Labile P was determined on each soil (1) by isotopic dilution (labile P^{32}), (2) by an anion exchange resin extraction (resin P), and (3) from an extrapolated value obtained from an adsorption/desorption isotherm (intercept P).

Labile P^{32} was determined following the procedure of Olsen and Sommers (1982) with some modifications. The modifications involved using a 1:25 soil-to-solution ratio and an equilibrating solution which was initially 4 x 10^{-6} M in carrier P^{31}. The extraction of P from soils using an anion exchange resin was performed in the laboratory of J. W. B. Stewart at the Saskatchewan Institute of Pedology. The procedure followed was that described by Sibbesen (1977). The EPC and intercept P were determined from adsorption/desorption isotherms using the method described by Kunishi and Taylor (1977).

Olsen, Bray I, and Mehlich I Soil Tests for P

Soil samples were sent to several State university soil testing laboratories where the Olsen (0.5N $NaHCO_3$ at pH 8.5), Bray I (0.025N HCl in 0.03N NH_4F), or Mehlich I (0.025N H_2SO_4 - 0.05N HCl) soil tests were performed on all soils in duplicate. The Olsen soil test (Olsen et al. 1954) was performed at the University of Nebraska, North Dakota State University, and Kansas State University; the Bray I test (Bray and Kurtz 1945) was performed at the Universities of Minnesota and Nebraska and at Kansas State University; and the Mehlich I soil test (Sabbe and Breland 1974) was performed at Auburn University and at the Virginia Polytechnic Institute and State University. Because there was good agreement among laboratories performing the same test (A. M. Wolf, unpublished data) only one set of values for each soil test was used in developing the relationships of soil test P with labile P and EPC. The soil test values from Nebraska, Kansas, and Virginia for the Olsen, Bray I, and Mehlich I soil tests, respectively, were used to develop these relationships.

RESULTS AND DISCUSSION

Comparison of Labile P Measurements

The equations describing the relationships among the three measurements of labile P are shown in table 2. While all relationships were good ($r^2 \geq 0.80$), the highest correlation was found between labile P^{32} and resin P ($r^2 = 0.88$). The slope of the equation describing the relationship between these two variables approached one, indicating that the labile P^{32} and resin P determinations are measuring proportional quantities of soil P. In contrast, the slopes describing the relationships of labile P^{32} and resin P with intercept P were 2.35 and 1.99, respectively, indicating that approximately one-half the quantity of labile P is estimated by the intercept P procedure in comparison to the labile P^{32} and resin P techniques.

As seen in table 2, the intercepts describing the relationships of both intercept P and resin P with labile P^{32} were significantly different from zero. In a preliminary experiment performed in this laboratory (A. M. Wolf, unpublished data) and as noted in experiments performed by others (Amer 1962, Amer et al. 1969), experimental difficulties involved in the determination of isotopically exchangeable labile P on low P soils may result in an overestimation of labile P. This effect may contribute to the significance of the intercepts observed in table 2.

Table 2. Equations describing the relationships among labile P measurements[1]

Equation[2]	r^2
Labile P^{32} = 5.75_* + 1.08 resin P	0.88
Labile P^{32} = 6.50_* + 2.35 intercept P	0.84
Resin P = 2.31_{ns} + 1.99 intercept P	0.80

[1]Labile P^{32} is labile P measured by isotopic exchange; resin P is P extracted with anion exchange resin; and intercept P is an estimate of labile P obtained from adsorption/desorption isotherms.

[2]* and ns indicate, respectively, that the intercept is and is not significantly different from zero at the 5 percent level of probability.

All three of the methods examined in this study are currently being used by researchers to evaluate the P status of soils. However, until experiments are performed on these soils evaluating the relationship between each of these three measurements of labile P and the biological availability of P, it is impossible to select the best measure of labile P.

Relationships Between Labile P and Soil Test P Measurements

As part of this study, relationships were developed among each of the three labile P measurements and the Olsen, Bray I, and Mehlich I soil test values. However, because of space limitations only those between isotopically exchangeable labile P and the soil test P values will be presented here. For the other relationships, the reader is referred to the supporting documentation for SWAM, Volume 3 (to be published).

The equations describing the relationships between labile P and soil test P on the soils from three geographic regions are given in table 3, along with the ranges of soil test values over which the equations were developed. The range of values for the Olsen, Bray I, and Mehlich I soil tests include those representative of low, medium, and high P fertility (Thomas and Peaslee 1973).

The Olsen and Bray I soil tests for P are the ones most commonly performed in the North Central States and, as seen in table 3, both of these soil tests were good predictors of labile P on the soils collected from this region ($r^2 \geq 0.88$).

On the southeastern soils, soil texture was found to have a significant effect on the relationship developed between labile P and Mehlich I P. This difference is likely related to the higher Fe oxide and clay content of the medium textured soils, which tends to neutralize the acid in the Mehlich extract (Thomas and Peaslee 1973). However, when the soils collected from this region were separated into medium and moderately coarse textured groups, Mehlich I P was found to be an excellent predictor of labile P ($r^2 \geq 0.91$).

The last group of soils examined were those from Pennsylvania and Ohio, where Bray I is the most commonly used soil test for P. As seen in table 3, Bray I was a good predictor of labile P ($r^2 = 0.82$) on the soils collected from these two States.

Relationships Between EPC and Soil Test P Values

The relationships between EPC and soil test P on the soils separated into geographic regions are shown in table 4. The EPC values of the north-central soils ranged from 5 to over 3000 ug/L, and the relationships between EPC and both the Olsen and Bray I soil tests for P over this range were found to be curvilinear. These relationships were most successfully described by performing log transformations on the Olsen and Bray I soil test P and EPC variables. As shown in table 4, the log of EPC and the logs of the Olsen and Bray I soil test P values were highly correlated ($r^2 \geq 0.82$), indicating that either of these tests may be used to adequately predict EPC over a wide range of values on this group of soils.

Table 3. Equations describing the relationships between labile P (y, ug/g) and soil test P (x, ug/g) on soils from three geographic regions

Geographic region	Soil test	Range of soil test values (ug/g)	Equation[1]	r^2
North Central	Olsen	4-40	$y = 5.14_* + 1.81\ x$	0.88
	Bray I	7-90	$y = 7.89_* + 0.80\ x$	0.93
Southeast	Mehlich I[2]			
	Medium	6-80	$y = 18.71_* + 0.94\ x$	0.92
	Coarse	6-81	$y = 2.12_* + 0.86\ x$	0.91
Pennsylvania and Ohio	Bray I	6-40	$y = 11.86_* + 0.61\ x$	0.82

[1]* indicates intercept is significantly different from zero.

[2]Medium and coarse refer to medium and moderately coarse textured soils, respectively.

While the log-log transformations shown in table 4 provide good relationships between the soil test measurements and the EPC values over the entire range of data, the EPC values of the north-central soils extend beyond the range considered necessary for the growth of most crops. In general, solution P concentrations in the range of 100 to 400 ug/L are the maximum required to produce optimal yields of crops grown on soils of medium and moderately fine textures (Kamprath and Watson 1980; Sanchez and Uehara 1980). Soils with EPC values less than 400 ug/L are therefore of greatest interest from an agronomic standpoint. The relationships between EPC and the Olsen and Bray I soil test P values were found to be approximately linear in the low (less than 400 ug/L) range of EPC values, and these relationships are described in table 4. Within this range both soil tests for P were found to be good predictors of EPC (r^2 values = 0.72).

On the southeastern soils, there was a good linear relationship (r^2 = 0.85) between P extracted by the Mehlich I soil test and EPC (table 4), with the exception of two outlier soils. One of the outliers was a Benndale fine sandy loam to which high rates of fertilizer P had been applied. The other was a Dickson silt loam which had received large quantities of manure. Neither of these soils was included in the regression analysis. The relationship between EPC and Mehlich I P given in table 4 was developed over EPC values ranging from 3 to 560

Table 4. Equations describing the relationships between EPC (y) and soil test P (x) on soils from three geographic regions

Geographic region	Soil test	Range of EPC and soil test P values: EPC (ug/l)	Soil test P (ug/g)	Equation[1]	r^2
North Central		Full range			
	Olsen	5-3242	4-39	$\log y = -0.15_{ns} + 2.15 \log x$	0.82
	Bray I	5-3242	7-90	$\log y = -0.46_* + 1.94 \log x$	0.85
		Low range			
	Olsen	5-400	4-23	$y = -38.40_{ns} + 14.30\ x$	0.72
	Bray I	5-400	7-42	$y = -30.41_{ns} + 7.16\ x$	0.72
Southeast[2]	Mehlich I	3-560	5-80	$y = -36.98_* + 5.65\ x$	0.85
Pennsylvania and Ohio	Bray I	1-100	6-40	$y = -20.48_* + 2.93\ x$	0.94

[1]* and ns indicate, respectively, that intercept is and is not significantly different from zero.

[2]Benndale soil receiving high rate of fertilizer P and Dickson soil receiving manure treatment not included in the analysis.

ug/L, which includes the range of solution P levels considered to be of greatest agronomic importance.

In contrast, only a small range of EPC values were represented on the soils collected from Pennsylvania and Ohio (table 4). In addition, only two soil series were represented in this group and both were classified as medium textured Alfisols (table 1). While the relationship developed between EPC and Bray I P on this group of soils was good ($r^2 = 0.94$), more data are needed on soils from this region before the relationships developed here can be extended to a larger group of soils having a greater range of EPC and soil test P values.

SUMMARY AND CONCLUSIONS

The biologically available P in soils is determined by the quantity of labile P and the concentration of P in the soil solution. While laboratory measurements of both labile P and solution P are time-consuming and expensive, State and commercial laboratories routinely perform low-cost soil tests for P for making fertilizer recommendations. The relationships developed in this study allow the labile P and solution P estimates to be made from soil tests which are routinely performed in different regions of the country.

The soil test P relationships with labile P presented here were developed using labile P measurements determined by isotopic dilution. However, labile P determined in this manner was found to be well correlated ($r^2 \geq 0.80$) with resin extractable P (resin P) and with the extrapolated values obtained from adsorption/desorption isotherms (intercept P).

When the soils used in this study were grouped into different geographic regions, the Bray I and Olsen soil tests for P were found to be good predictors of both EPC and labile P on the north-central soils ($r^2 \geq 0.72$); the Mehlich I soil test was found to be a good predictor of these two parameters on the southeastern soils ($r^2 \geq 0.85$); and the Bray I soil test for P was a good predictor of labile P and EPC on the two soils collected from Ohio and Pennsylvania ($r^2 \geq 0.82$).

The relationships developed in this study make use of the readily available low-cost soil test P methods as well as the considerable soil test P data bases already available to provide P input data needed for models used to predict P uptake by plants and to estimate the loss of P from agricultural land.

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PREDICTION OF MAJOR ION CONCENTRATIONS IN ARID LAND SOILS USING EQUILIBRIUM AND KINETIC THEORIES

D. L. Suarez*

INTRODUCTION

Accurate predictions of major ion concentrations in and below the rootzone are necessary for good irrigation management when irrigating with saline waters. Predicting the effects of different management strategies on overall water quality and composition also requires that we understand the controls on major ion concentrations. Over the past 15 years many models have been developed. Typically these range from empirical, site-specific models that are suitable only for a single irrigation management and irrigation water, to models that emphasize water-flow and evaporation but which do not consider dissolution or precipitation (Bresler and Hanks 1969), to models which consider equilibrium with respect to $CaCO_3$ or gypsum but do not predict water movement (Oster and Rhoades 1975), to models which consider equilibrium chemistry, ion exchange and transient water flow (Jury et al. 1978, Robbins, et al. 1980, Shaffer and Larson 1982). Some models require extensive input data, such as CO_2 pressure, exchangeable ion concentrations with depth, hydraulic conductivities and moisture contents, leaching fraction, water uptake distribution, and irrigation water composition.

COMPARISON OF THREE MODELS

The following discussion will compare the simple model, which does not consider precipitation, with both an equilibrium model and the new model which uses kinetic rather than equilibrium chemistry. Earlier work (Suarez 1977) has demonstrated that the equilibrium chemical assumption is not realistic to predict solution chemistry below the root zone. The important variables necessary for accurate predictions can best be demonstrated by a comparison of the models with actual data.

Experimental Data

The experimental data for the comparison are taken from field lysimeters 1.5 m deep and 9 m^2, cropped to alfalfa. For each of the lysimeters different water composition, irrigation frequency, and leaching fractions are maintained. For purposes of simplicity we will examine only data where ion exchange is relatively minor. At each depth, 0.3, 0.6, 0.9, and 1.2 m, the data presented are averages from three soil water extractors or three air samplers. The extractors are of the type described by Suarez and Wood (1984) such that degassing and pH errors are negligible.

Figure 1 shows several variables as functions of time during an irrigation cycle (irrigations on day zero and day 13). The P_{CO_2} varied during the irrigation cycle and was greater when the soil was wet than when dry. The Cl concentration increased as a result of evapotranspiration; and the HCO_3 concentration decreased, thus indicating precipitation. Since Ca >> HCO_3, Ca concentrations still increased despite precipitation due to evapotranspiration. As the plot of pIAP, $p(a_{Ca^{2+}} \cdot a_{CO_3^{2-}})$ indicates, the soil solutions are more than 10-fold supersaturated with respect to calcite (pK_{sp} = 8.48, Jacobson and Langmuir 1974). Also, the degree of supersaturation varied during an irrigation cycle, becoming most supersaturated just before an irrigation as the soil was dried out. Figure 2 shows variation in the pIAP with depth, again indicating lack of equilibrium and a kinetic control on Ca concentrations. These data indicate that maximum precipitation (based on a comparison of expected with measured Ca concentrations) occurred when the solutions were most supersaturated.

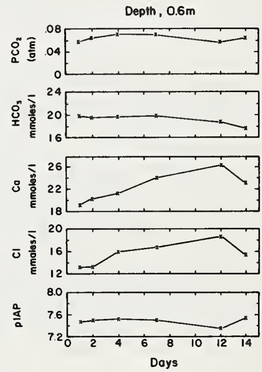

Figure 1 -- Change in soil water composition with time after irrigation. Values show the average from three extractors at 0.6-m depth. A second irrigation was applied on day 13.

Solution composition is very dependent on CO_2 concentration (data not shown). The CO_2 concentration is seasonally dependent, likely due to temperature variations, as shown in figure 3. The seasonal dependence show in figure 3 and the interaction of CO_2 and moisture contents (figure 1) indicate that use of a single CO_2 value to predict solution compositions, can lead to large errors. A separate dynamic model is required to predict CO_2 in the root zone.

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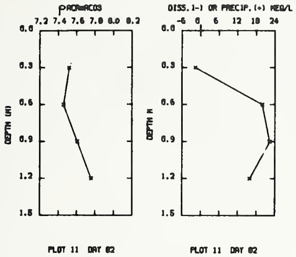

Figure 2.--(a) $CaCO_3$ ion activity product with depth for plot 11, irrigated daily. Values at each depth represent the average from three extractors.

Figure 2.--(b) Dissolution - precipitation values representing differences between Ca values measured at that depth and Ca values expected, based on Ca values at the previous depth and the concentration factor (Cl ratio) between the two depths.

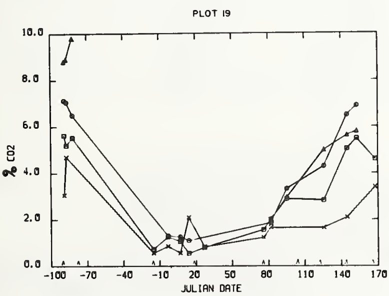

Figure 3.-- Percent CO_2 concentration with time relative to Jan. 1, 1983, where X, □, O, Δ represent the concentrations at the 0.3-m, 0.6-m, 0.9-m and 1.2-m depths, respectively. Each point represents the average value from three air samplers.

Kinetic $CaCO_3$ Model

The kinetic $CaCO_3$ model developed to predict soil solution composition requires input of irrigation water composition, moisture content, P_{CO_2} distribution with depth, leaching fraction or concentration factors with depth, and calcite surface area. It calculates travel times using the K vs. θ relationship from Bresler (1983 personal communication) for Pachappa soil shown in figure 4 and assuming piston displacement. The model also calculates dissolution or precipitation rates, solution pH, and composition with depth or time (steady state). The ion exchange subroutine requires input of exchangeable sodium percent (ESP) with depth and the cation exchange capacity (CEC).

Calcite reaction rates were predicted with the following relationship from Plummer et al. (1978).

$$R = 0.051\,[H^+] + 3.45\times10^{-5}\,[H_2CO_3] + 1.18\times10^{-7} - K_4\,[Ca^{2+}][HCO_3^-]$$

$$\text{where } K_4 = \frac{K_2}{K_c}\left[0.511 + \frac{1}{[H_s^+]}\left(3.45\times10^{-5}\cdot[H_2CO_3] + 1.18\times10^{-7}\right)\right]$$

R is expressed in $mmoles\cdot cm^{-2}\cdot sec^{-1}$, brackets denote individual ion activities, K_2 is the second dissociation constant of carbonic acid, K_c is the solubility product of calcite and $[H_s^+]$ the H^+ activity at the calcite surface. The value of $[H_s^+]$ is obtained by taking the existing solution composition and computing what its composition would be when in equilibrium with calcite. The model uses a concentration-time relationship for applied water rather than concentration vs. depth as in a dynamic water flow model. For steady state flow the water-time relationship can be substituted for the water-depth relationship. This assumes that the chemical composition of the soil water at depth X+1 can be obtained by multiplying the concentrations at depth X by the differences in the concentration factor ($Cl_{x+1}/Cl_{irr} - Cl_x/Cl_{irr}$), calculating the travel times to the next depth, based on θ and accounting for precipitation during that time.

Experimental Data vs. Predicted Data:

The following analysis includes a comparison of the experimental data with values predicted by an equilibrium calcite model, the kinetic model just described, and a model that ignores precipitation or dissolution. Only experimental data which did not show substantial ion exchange were selected for analysis. This was done to separate the

effects of precipitation from the effects of ion exchange. The models were also run without including ion exchange. For the simulations shown in figures 5 and 6, the models used the water content (θ) from neutron probe measurements, the known irrigation water composition, and concentration factors at each depth calculated from measured chloride ratios. A calcite surface area of $1 m^2$ per liter of solution was used in all kinetic simulations; it was not used as an adjustable, fitting parameter.

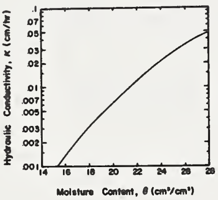

Figure 4.-- Relationship between hydraulic conductivity, K, and volumetric moisture content, θ, for Pachappa soil, as determined by Bressler 1983 (personal communication).

As shown in figure 5, measured alkalinity decreased slightly with depth. The predicted equilibrium values were too low by a factor of 2 to 3. The kinetic model was the best predictor, with values midway between the equilibrium and measured values. The worst predictor was the no precipitation model, which yielded alkalinities of 70 $meq \cdot L^{-1}$ at 1.2 m as compared to a measured value of 12 $meq \cdot L^{-1}$. The data shown in figure 5 are from plot 11, which has a low leaching fraction, slow travel time, and very substantial calcite precipitation. Figure 6 shows the good simulation of measured pIAP of $CaCO_3$ with depth predicted by the kinetic model. The kinetic model also correctly predicts the increasing pIAP with depth. The equilibrium model gives a constant pIAP value of 8.47, independent of depth, CO_2, or concentration factor.

For most field conditions only estimates of the overall leaching fraction are available. These estimates are based on volume of water infiltrated and estimated evapotranspiration, or possibly chloride concentrations at the bottom of the rootzone. Shown in figure 7 is a comparison of measured chloride concentration with depth and chloride concentration predicted using water budget data for the lysimeter and the exponential

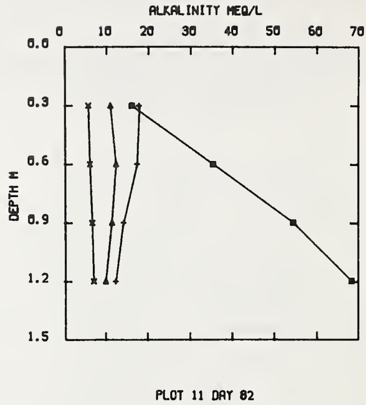

Figure 5.-- Comparison of measured HCO_3 expressed as $meq \cdot L^{-1}$ alkalinity with depth (+), with that predicted from the equilibrium model (*), kinetic model (Δ), and the no precipitation model (◘).

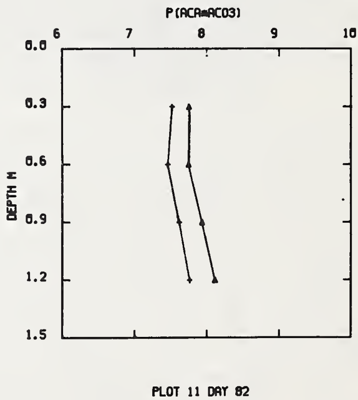

Figure 6.-- Comparison of measured pIAP of $CaCO_3$ with depth (+) to predicted pIAP values from the kinetic model (Δ).

water uptake relationship described by Hoffman and van Genuchten (1983). As shown, incorporation of the exponential water uptake equation instead of the measured water uptake function introduces a substantial error. A further comparison of the various models is shown in figure 8. The kinetic model again is the best predictor of alkalinity concentrations with depth. The

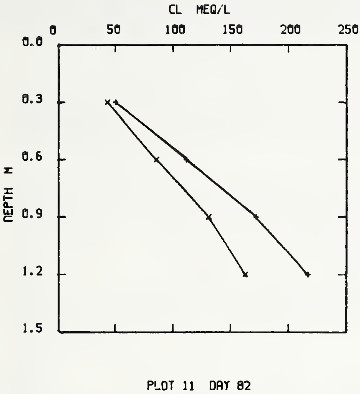

Figure 7.-- Measured chloride distribution with depth (+) compared to chloride predicted using an exponential water uptake model (X).

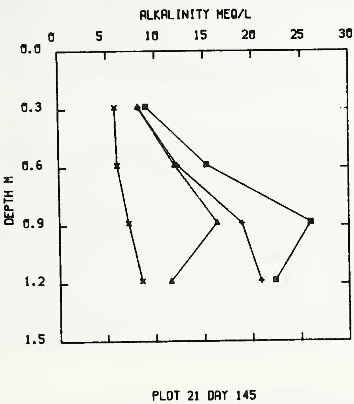

Figure 8.-- Comparison of measured HCO_3 expressed as $meq \cdot L^{-1}$ alkalinity with depth (+) with that predicted from the equilibrium model (X), kinetic model (Δ), and the no precipitation model (□).

errors at the 1.2-m depth are due to the inadequacy of the water-flow model. The corresponding chloride concentrations at the 1.2-m depth (not shown) are lower than the chloride concentrations at the 0.9-m depth. Evidently, leaching fractions were increasing when this plot was sampled; thus it is not reasonable to consider the water composition at 1.2-m as having been derived from the water composition at 0.9-m, as the model does.

Further development of the model will consist of coupling the kinetic and ion exchange model with a dynamic flow model, allowing prediction for non-steady-state water flow.

The application of the kinetic model is not restricted to arid land environments under irrigation. It can be used to predict the change in exchangeable sodium of a calcareous soil (or a noncalcareous one to which $CaCO_3$ has been added) under rainfall or irrigation. Although calcite is regarded as a sparingly soluble mineral, large quantities of $CaCO_3$ can be dissolved for reclamation in the presence of high soil CO_2 concentrations and high exchangeable sodium. In areas of Ca deficiency or low soil pH, addition of $CaCO_3$ is a common practice. Under these conditions the equilibrium model will not always be an accurate predictor -- especially if large particles of calcite are used.

The effect of calcite surface area on solution composition is also shown in the following steady state simulation, (omitting ion exchange and changes in water flow). For purposes of illustration we have assumed the soil P_{CO_2} distribution given in figure 9, a volumetric

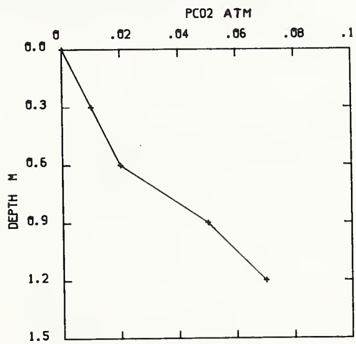

Figure 9.-- Values of P_{CO_2} with depth used in the kinetic simulations shown in figures 10, 11 and 12.

moisture content of 0.25, rainfall with a Ca concentration of 0.2 $meq \cdot L^{-1}$, a soil water concentration factor of 1.5 at the bottom of the root zone, and calcite surface areas of 0.5, 5 and 500 m^2 per liter of soil solution. Figure 10 shows the predicted Ca concentration with depth for different calcite surface areas. Clearly, large differences between the 0.5-m^2 and 5.0-m^2 surface area curves are present, while the curves for 5.0 m^2 and 500 m^2 are quite similar. The equilibrium model predicts values close to those shown for 500 m^2 of calcite. Figure 11 shows the HCO_3 concentrations for the same three different

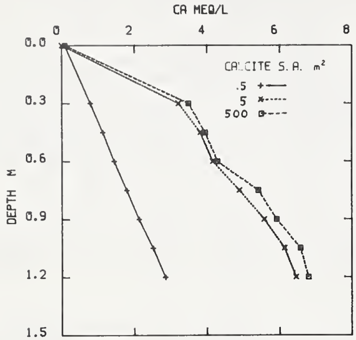

Figure 10.-- Calcium concentrations with depth predicted by the kinetic model using the input calcite surface areas of 0.5 (+), 5.0 (*) and 500 (□) $m^2 \cdot L^{-1}$ of soil solution.

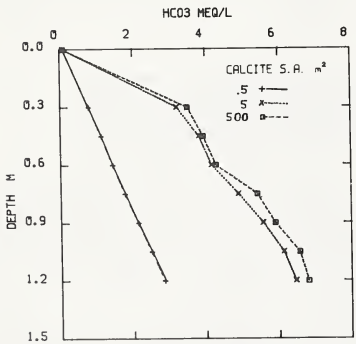

Figure 11.-- Predicted HCO_3 concentrations with depth using the input calcite surface areas of 0.5 (+), 5.0 (*), and 500 (□) $m^2 \cdot L^{-1}$ of soil solution.

surface areas. Since ion exchange did not occur, these values are similar to those presented for the calcium concentrations.

The pIAP values ($a_{Ca}{}^{2+} \cdot a_{CO_3}{}^{2-}$) shown in figure 12 indicate that all soils were calcite undersaturated at the surface but that at high calcite surface areas the soils quickly approached saturation (pIAP=8.5). In this instance, depending on surface area, the equilibrium model could provide either a good or very poor prediction of solution composition.

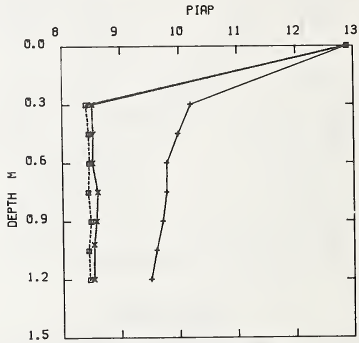

Figure 12.-- Predicted pIAP values for $a_{Ca}{}^{2+} \cdot a_{Ca}{}^{2-}$ with depth using the input calcite surface areas of 0.5 (+), 5.0 (*), and 500 (□) $m^2 \cdot L^{-1}$ of soil solution.

Although the kinetic model leads to an improved predictive ability, as compared to the equilibrium model, several limiting factors still prevent accurate predictions. For steady-state conditions these include prediction (rather than measurement) of P_{CO_2} distribution with depth in the soil. Predicting P_{CO_2} will require a dynamic model, with the main variables being soil temperature, moisture content and root activity. Additional limiting factors include prediction of the water uptake distribution and, especially for dynamic simulations, the cation exchange capacity and initial exchangeable sodium with depth.

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MICROBES AND MICROBIAL POPULATION DYNAMICS AS RELATED TO PESTICIDE DEGRADATION IN SOIL

Philip C. Kearney and Donald D. Kaufman[1]

INTRODUCTION

Any environmental modeling system that includes pesticide persistence as a program component must be prepared to deal with the important and sometimes variable role that soil microorganisms play in the degradation process. Classical soil microbiology has provided us with methods for measuring degradation, enumerating and identifying the causative organisms, and elucidating the metabolic pathways. The advent of modern biochemical genetics has provided us with a keener insight into the adaptation process by which microbes can form degradative enzymes and derive energy for other cellular processes. All of this research has led to a series of generally accepted values for expressing persistence in terms of half-lives or 90 percent disappearance times.

Certain events have occurred over the last decade that may cause problems in dealing with persistence as a modeling constant in the future. The reasons for this uncertainty are complex but are primarily due to evolutionary processes in the marketplace and in the soil microbial community. Simply stated, the kinds of compounds we are using in pest control programs have changed and this has had a profound effect on the soil metabolic processes and hence persistence. A brief overview of some of these market trends and the principles of biological pesticide degradation need to be reviewed and these principles interpreted in terms of modern biochemical genetics. Finally a discussion of what we now have termed "problem soils," where degradation is enhanced, will be considered.

MARKET TRENDS

There have been tremendous changes in the amounts and kinds of pesticides used in American agriculture over the last two decades. Table 1 shows the U.S. production, sales, and value of pesticides by class for the years 1962, 1972, and 1980 (Kearney 1982). Unfortunately, we have limited 1982 data, but the 1980 data serve as good indicators of current trends. In 1962, we were largely an insecticide-producing nation. At that time, 63 percent of the pesticides produced were insecticides, or roughly 461 million pounds of insecticides were produced out of a total of about 730 million pounds of pesticides. In 1964, the chlorinated hydrocarbons (DDT, aldrin, dieldrin, and others) represented 70 percent of insecticide use, the organophosphates 20 percent, and the carbamates 8 percent (Schaub 1984).

U.S. production and sales of pesticides have increased every year since 1962 except for 1969 and 1970, when there were declines in both production and sales. Pesticide production reached a high in 1975 at 1.6 billion pounds that has not since been exceeded.

By 1980, the pattern had changed considerably from 1962, and now the United States is largely a herbicide-producing nation. The figures show that herbicides occupy about 55 percent of the market, or roughly 806 million pounds of herbicides were produced out of a total of 1.46 billion pounds of pesticides. The value of sales has risen from $346 million in 1962 to well over $4 billion in 1980.

Over this 20-year period then, we have seen a tremendous increase in the use of pesticides, which has almost doubled, and a changing pattern of use in which the herbicides now dominate the market. Based on a 1982 survey, it is estimated that herbicides were used on nearly 220 million acres, or on a crop basis, 95 percent of the corn acreage, 93 percent of the soybean and peanut acreages, 97 percent of the cotton acreage, and 98 percent of the rice acreage were treated with herbicides (Schaub 1984).

These market trends have changed the kinds of pesticides introduced into the soil environment. Many persistent chlorinated hydrocarbon insecticides have been replaced by the more biodegradable carbamate and organophosphate compounds. Whether these usage shifts have affected the soil microbial community is unknown. There is evidence that continued use of certain biodegradable pesticides on some soils is influencing metabolism.

PRINCIPLES OF MICROBIAL METABOLISM

The kinetics of biological pesticide degradation are well studied (Loos 1975) and generally follow the patterns depicted in figure 1. Initially, a small but fairly rapid decrease occurs in pesticide concentration due to soil sorption processes. This phase is followed by a lag phase, during which no appreciable change in pesticide concentration occurs. The length of the lag phase is substrate dependent. A period of rapid substrate disappearance follows the lag phase. Subsequent additions of the same substrate or a structurally related substrate to an adapted soil disappear rapidly without a lag phase and generally obey first-order kinetics.

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Table 1. Production of pesticides in the United States in the past twenty years

Date	Activity	Fungicides	(%)	Herbicides	(%)	Insecticides	(%)	Totals
		(Figures in 1,000's)						
1962	Production	117,479	16	150,888	21	461,351	63	729,718
	Sales in lb	97,589	15	95,209	15	441,164	70	633,962
	Sales values (dollars)	45,816	13	92,117	27	208,368	60	346,301
1972	Production	142,812	12	451,311	39	563,575	49	1,157,698
	Sales in lb	128,517	12	353,583	35	539,465	53	1,021,565
	Sales values (dollars)	82,164	8	628,958	58	380,586	35	1,091,708
1980	Production	156,213	11	805,663	55	506,326	34	1,468,202
	Sales in lb	146,339	10	767,745	55	492,237	35	1,406,321
	Sales values (dollars)	290,165	7	2,558,287	63	1,230,046	30	4,078,498

Three important principles have evolved from this early work:

1. The length of the lag phase is compound dependent and very reproducible.

2. The biochemical entity responsible for enzyme formation is fairly stable in the soil environment.

3. Compounds structurally similar to the inducer molecule when added to an adapted soil are metabolized without a lag phase. This is called cross adaptation.

In terms of modern microbial genetics, we are beginning to understand how these principles operate at the molecular level. The code for degradative enzyme synthesis is contained on DNA molecules in soil microorganisms. The single cell or prokaryotic bacterium contains a single chromosome or genophore. There is increasing evidence that movable genetic elements may alter the DNA sequences and, consequently, change the expression of genes such as those encoding pesticide degradative enzymes in soil microorganisms. These extrachromosomal elements or ECE's are additional genetic elements or pieces of DNA external to a cell's chromosome. Many ECE's can be classified into plasmids and viruses, which further contain movable genetic elements, such as insertion sequences and transposons. From a pesticide standpoint, plasmids are the best studied of the ECE's. These ECE's have important implications in the biological metabolism of pesticides and the principles discussed previously.

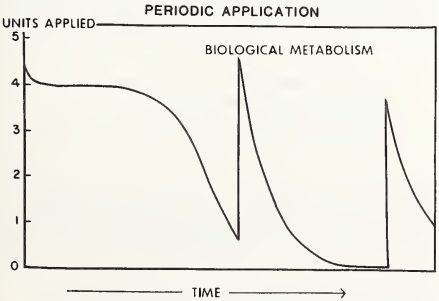

Figure 1.--Kinetics of biological pesticide degradation.

Plasmids are small circular DNA polymers that carry genetic information. They range in size from small (2,250 nucleotide pairs) to large complex structures that may contain 400,000 nucleotide pairs. Plasmids are autonomous or independently replicating genetic units within the bacterial cell. They are classified as conjugative and nonconjugative based on their ability to transfer themselves at time of conjugation or cell-to-cell fusion. An excellent review on plasmids has been prepared by Cohen (1976).

Plasmids play an important role in pesticide metabolism in soils. Reports are now appearing on the isolation and characterization of degradative plasmids for a number of pesticides. Two classes of biodegradable herbicides have received major attention, that is, the chlorinated aliphatic acids (dalapon and trichloroacetate) and the phenoxyacetic acids (2,4-D, MCPA, and 2,4,5-T). As studies progress with isolated plasmids and the enzymes derived from these degradative plasmids, certain fundamental principles elucidated from the earlier soil kinetic studies now can be explained on the basis of ECE's.

Enzymic studies with microorganisms known to contain degradative plasmids generally tend to exhibit a broad substrate specificity. For example, the dehalogenases isolated by Motosugi et al. (1982) demonstrated a broad specificity for the 2-halogenated aliphatic carboxylic acids whose carbon chain lengths were less than five. Likewise, the early bacterial enzyme extracts isolated from an Arthrobacter sp. for the halogenated phenoxyacetic acids dehalogenated the 2,4-dichloro, 2-methyl-4-chloro, and 2- or 4-chloro derivatives of phenoxyacetic acid esters, with evidence that the chlorinated phenols were intermediates prior to ring cleavage and chloride ion release into the medium (Loos et al. 1967). Cross adaptation then can be explained on the basis that degradative enzymes evolved from plasmids are generally specific for a particular linkage in a molecule, but the rate of catalysis is governed by steric and inductive effects around that particular linkage.

The early observation that the components responsible for enzyme formation are fairly stable in the soil environment also can be explained by plasmid mobility. Due to the dynamic nature and mobility of ECE's, large-scale DNA sequences can be lost, gained, and transposed within and between bacterial species. Hypothetically, a gene originating as a segment of chromosomal DNA in one species of soil bacteria can translocate to a conjugative plasmid and pass into the genetic material of a second species, where the gene may remain as part of an ECE or migrate to a chromosomal locus. The longevity of the gene is then perpetuated by the survival of resistant organisms in the microbial community. Don and Pemberton (1981) isolated and characterized the biophysical and genetic properties of six plasmids encoding the degradation of 2,4-D and MCPA from Alcaligenes paradoxus and A. entrophus. Four of these plasmids transferred freely to a number of other bacteria via conjugation.

These are the processes that influence microbes and microbial population dynamics as related to pesticide degradation in soils. An extensive review of ECE's and the pesticide adaptation process has been prepared by Kearney and Kellogg (1984).

PROBLEM SOIL

The biological principles of pesticide metabolism outlined in the previous section provide a fundamental basis for understanding a problem that could complicate any attempt to model or treat in a systematic manner pesticide persistence. In certain geographic regions, and in certain soils, specific classes of soil-applied pesticides are failing to control their target pests. These are termed "problem soils." The reasons for these performance failures are complex and may relate to application difficulties,

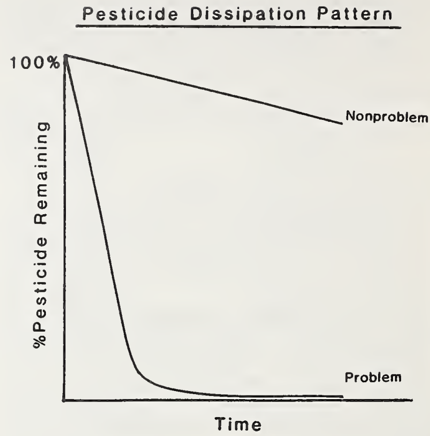

Figure 2.--Pesticide dissipation in a problem and nonproblem soil.

development of host resistance in the pest, and low population pressures at the time of application. While these may be contributing factors, there is growing evidence that enhanced soil microbial metabolism is the major contributing factor. A typical response showing the kinetics of breakdown in a problem and nonproblem soil is shown in figure 2. Conceptually, the kinetics of a problem soil bears some similarity to the rapid decline phase observed in an adapted soil (fig. 1). It suggests that some evolutionary event has triggered a segment of the microbial population to form enzymes to metabolize the added pesticide.

A number of reasons have been advanced to account for the problem soil phenomenon (Kaufman et al. 1983), and they include--

1. The repeated use of the same pesticide annually on the same soil.

2. The chemical similarities of several pesticides used on the same crop.

There is also speculation that the replacement of the more persistent, less degradable chlorinated hydrocarbon pesticides, in the case of the insecticides, with the more biodegradable alternatives may be a contributing factor.

Problem soils were first encountered with the thiocarbamate herbicides (Kaufman and Edwards 1983). The similarity of many structurally related agricultural chemicals suggests that one pesticide may induce enzyme(s) capable of degrading a chemically related compound added simultaneously or subsequently to the same soil.

The chemical linkages in pesticides that appear to be susceptible to cross adaptation in these problem soils include the carbamate -N-CO-O, urea N-CO-N, amide N-CO-C, ester COO-C, thiocarbamate N-CO-S, and dithiocarbamate N-CS-S bonds. The appearance of rapid microbial metabolism of these compounds in soils treated previously, and in some cases several years previously, again tends to emphasize the persistent nature of the responsible genetic elements in nature and implicate plasmids as a mechanism endowing persistence and mobility. Research is currently in progress to determine what agronomic practices or inhibitors are necessary to protect this potentially large number of pesticide compounds from further losses in effectiveness.

The exact magnitude of the problem soil phenomenon is as yet unknown. It is also not known whether the problem is confined to certain pesticide-soil-geographic combinations, or whether it is subject to further expansion as certain conditions are met with regard to the optimum combinations for enhanced metabolism. The programmer attempting to model any agricultural management system that quantifies the contribution of agricultural chemicals to production or pollution programs must be aware of the future potential for, or existence of, enhanced microbial metabolism of biodegradable pesticides and changing market trends.

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PESTICIDE DISSIPATION RATES FROM FARM PONDS AND SMALL IMPOUNDMENTS

Ralph G. Nash and Allan R. Isensee[1]

INTRODUCTION

Prediction of pesticide dissipation from a pond is predicated on the premise that a pesticide mass balance exists and that changes in the pesticide concentration of pond water can be calculated for any given time. This means that the amount of pesticide entering and leaving a pond and the dominant pond processes that alter the amount of pesticide in the water are known or can be estimated. Pesticide partitioning between adsorbed and soluble phases can be estimated from several empirically derived equations. Pesticide dissipation rates can be determined by periodic measurements or by simulation of the dominant dissipation processes. Monitoring the pesticide is probably better, but the time and expense of monitoring thousands of ponds would overwhelm our resources. Further, it is important to estimate what will happen under certain land management practices. To do this, the pesticide concentration in water at any given time must be estimated. This paper will identify and briefly discuss important pond pesticide processes--specifically, the several pesticide partitioning and loss pathways. Further, it will identify methods for estimating partitioning and the rates at which a pesticide will be lost by each pathway.

PARTITIONING (K)

Exclusive of the stream and stream sediment and pesticide load, the most drastic and rapid change in pond pesticide processes usually occurs immediately after the pesticide enters the pond. The pesticide will re-equilibrate between the water and abiotic and biotic surfaces, thus reducing the pesticide concentration in the pond water.

The degree of sorption (K_d) to abiotic surfaces depends upon the hydrophobicity of the pesticide; the more hydrophobic the greater the sorption. K_d is defined as

$$K_d = P_s(P_w)^{-1} \quad (1)$$

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where P_s = pesticide concentration on sediment ($\mu g\ g^{-1}$) and P_w = pesticide concentration in water ($\mu g\ g^{-1}$).

Several methods are available for estimating K_d. The most useful is based on the organic carbon (K_{oc}) of the suspended solids and sediments:

$$K_{oc} = 100K_d(\%\ OC)^{-1} \quad (2)$$

Because it (where % OC = percent organic carbon) can be estimated empirically from pesticide octanol-water (K_{ow}) partitioning or water solubility (K_w) (Karickhoff et al. 1979; Hassett et al. 1980),

$$K_{oc} = 0.55\ K_{ow} \text{ or } = 18{,}750\ K_w^{-0.69} \quad (3,4)$$

The other partitioning process is bioconcentration (K_{bcf}):

$$K_{bcf} = P_o(P_w)^{-1} \quad (5)$$

where P_o = pesticide concentration in organisms ($\mu g\ g^{-1}$).

This factor expresses the potential for a pesticide to accumulate in aquatic organisms and depends upon the pesticide lipophobicity, hydrophobicity and metabolic characteristics. Like K_d, K_{bcf} can be estimated from K_{ow}, K_{oc}, and K_w constants (Veith et al. 1979; Kenaga and Goring 1978):

$$K_{bcf} = 0.2\ K_{ow}^{0.85}, = 618\ K_w^{-0.564}, \text{ or } = 0.026\ Koc^{1.12} \quad (6\text{-}8)$$

However, for future considerations, because both abiotic and biotic sorption are a function of their (abiotic and biotic) mass and because sorption is not instantaneous (sorption in ponds is likely slower than demonstrated in laboratory studies), they probably should be treated kinetically rather than thermodynamically. If so, it would appear that pseudo-second-order kinetics would apply, being positive for absorption or accumulation and negative for desorption or elimination.

DISSIPATION RATES (k)

The several pathways for pesticide loss from pond water are:

Volatilization	(k_v)
Photolysis	(k_p)
Hydrolysis	(k_h)
Reduction/oxidation	($k_{r,o}$)
Complexation	(k_c)
Polymerization	(k_m)
Diffusion	(k_f)
Biodegradation	(k_b)
Bioelimination	(k_e)

However, rarely do all of these loss pathways occur for any one given given pesticide. Further, k_e and k_f are usually of little importance. Several of the rate constants (k_v, $k_{r,o}$, k_h, k_p, k_c, k_m) may be reversible, given the proper conditions and energy; but under practical pond conditions the reversibility is so small that it can ignored. For example, k_r is usually not important in pond water but can be important in microbiologically active pond sediments. Both k_r and k_o are usually associated with other dissipation processes, that is, biological reduction or oxidation and photo-oxidation. Therefore, k_r and k_o probably can be ignored under most circumstances.

Polymerization (k_m) probably rarely ever occurs in pond water because pesticide concentration is too low, and therefore can be ignored. Complexation (k_c) may be extremely important when pesticides chemically bind to clay minerals and biotic materials or when irreversibly conjugated biologically.

It is generally assumed that some dissipation processes can be expressed as or reduced to pseudo-first-order kinetics (Burns et al. 1979; Harris 1982a, 1982b; Mackay and Paterson 1981; Thomas 1982; Zepp et al. 1975). By combining and omitting some of the pond pesticide processes and ignoring spatial gradients, the following equation can be written:

$$\frac{dP_w}{dt} = -(k_v + k_p + k_h + k_b + k_c)\ P_w \qquad (9)$$

[Diffusion (k_f) is a special case and will be discussed later]. However, with the availability of computers and the appropriate input values, there is no reason why higher order kinetics could not be used to increase the accuracy of pesticide loss from a pond. On the assumption that pseudo-first-order loss rates (k) prevail, and by combining and omitting some of the pond pesticide processes, the following can be written:

$$C_d = P_w e^{-\Sigma kd} \qquad (10)$$

where C_d = pesticide concentration in pond water and d = any given day.

DETERMINING OR ESTIMATING RATE CONSTANTS (k)

The two common methods for determining dissipation rate constants are to measure periodically the pesticide amount with time and then obtain a rate constant by determining an equation that fits the data, or to estimate a rate constant from theoretical considerations of the several ideal compartments of a system. Estimation has considerable appeal because it is less expensive and time consuming. A discussion of estimating rate constants has been thoroughly reviewed by Lyman et al. (1982). A more detailed discussion of estimating k values is presented in a supporting paper "The SWAM Conceptual Process for Pesticides and Their Dissipation" by the same authors. All rate constants (k) are on a per-day basis.

Rate of Volatilization (k_v)

Pesticide volatilization from a pond depends upon water and air temperatures, wind velocity, and pesticide diffusion through both the water and air [usually referred to as the two-boundary layer (Liss and Slater (1974)]. However, as indicated by Thomas (1982), volatilization can often be reduced to pseudo-first-order kinetics because measured loss rate reflects the resistance of the boundary layer.

Rate of Photolysis (k_p)

Pesticide photolysis rate in water has been reviewed by Harris (1982b)) and Burns et al. (1979). Most photolysis rates have been determined under laboratory conditions, which usually are much different than under field conditions. Light attenuation (from pond depth), turbidity, season and latitude, and cloud cover all reduce the energy available for photolysis. Wolfe et al. (1982) provide equations for light attenuation and cloud cover. Conversely, Zepp and Schlotzhauer (1983) have shown that certain algae-enhanced photodegradadation occurred through photo-induced pesticide absorption to the algae.

West et al. (1983) determined dissipation half-lives of fluridone, an aquatic herbicide, in 40 ponds scattered over North America. They found that latitude had little effect on the photodegradation of fluridone and that pond depth explained only 63% of the variation. By incorporating dissolved oxygen and turbidity into the equation, instead of pond depth, the regression equation for fluridone half-life was greatly improved.

Rate of Hydrolysis (k_h)

Pesticide hydrolysis rate in water has been reviewed by Harris (1982a) and Burns et al. (1979). Hydrolysis rates for several pesticides have been determined and methods have been devised for converting laboratory hydrolysis rates to correspond to pond hydrolysis at different temperatures (Harris 1982a).

Rate of Biodegradation (k_b)

Biodegradation is one of the more complicated rate processes to describe in natural waters, because several species may be present and there is a fluctuating species population density, depending upon all the pond parameters, as well as the pesticide. Biodegradation (microbial) is not only time dependent but is proportional to the microbial population. Therefore, biodegradation rate is usually found by Monod kinetics (Paris et al. 1981; Scow 1982). However, in ponds where pesticide concentration is low, Monod kinetics reduces to pseudo-second-order kinetics. Further, in those cases where the pesticide is not the primary source of carbon, but tertiary or quartic, the degradation rate most likely reduces to pseudo-first-order kinetics, as shown in figure 1.

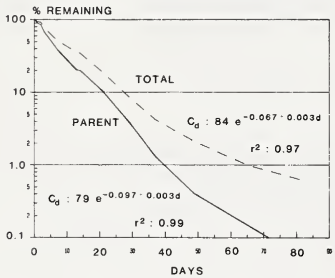

Figure 1.--Dissipation of chlorpyrifos-methyl (parent) and chlorpyrifos-methyl plus 3,5,6-trichloro-2-pyridinol (total) in lake water and clean soil at 15°C (Szeto and Sundaram 1982).

Rate of Diffusion (k_f)

Diffusion of pesticides from sediments into water probably cannot be separated from sorption partitioning for most pesticides. Diffusion may become important in those situations where a large quantity of a long-lived pesticide is washed into a pond along with a heavy silt load. In such a situation where most of the pesticide is partitioned into the sediment, the diffusion of the pesticide back into the water would be very slow over a long period of time. Presumably, the equations given by Jury et al. (1980) for liquid diffusion could be used for transport of pesticide from sediment to water.

Rate of Complexation (k_c)

Complexation as defined here are all those processes which essentially bind a pesticide to abiota or biota such that it will not desorb from, be excreted from, or diffuse out of solid material into the pond water. Complexation can be considered as encompassing "bound residues" and pesticide losses that cannot be explained or accounted for. The complexation rate (k_c) will be assumed to be pseudo-first-order.

ESTIMATING PESTICIDE PARTITIONING AND DISSIPATION FROM A POND

Several mathematical models exist for determining pesticide partitioning in a pond and subsequent dissipation (Burns et al. 1979; De Coursey 1982; Mackay and Paterson 1981; papers in this symposium and others). Nearly all use some form of first-order kinetics to estimate pesticide dissipation.

The several dissipation rates (first-order) can be summed and used in equation (10) to determine pond water pesticide concentration provided an initial concentration is known.

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METHODS OF ESTIMATING PESTICIDE SORPTION COEFFICIENTS FOR SOILS AND SEDIMENTS

Richard E. Green[1]

INTRODUCTION

The importance of pesticide sorption from solution regarding the environmental fate of pesticides is widely recognized. The physical-chemical nature of the sorption process for a variety of chemicals on organic and mineral surfaces has been exhaustively reviewed (for example, Hamaker and Thompson 1972, Green 1974). Understanding the mechanisms of specific pesticide-sorbent interactions does not, however, help substantially in assessments of pesticide disposition and impact in the environment, unless sorption information is integrated with other information on fate processes. Complex mathematical models have been developed to accomplish this integration, but with considerable simplification in the description of individual processes (for example, the ARM and HSPF models of EPA or the CREAMS model of ARS/USDA). The incorporation of a large number of processes (physical, chemical, and biological) into a complex model usually requires sacrificing detail in the description of any given process. The principal reason for simplification is the lack of independently measured input parameters needed in a detailed mathematical description of the process for a variety of relevant environmental conditions. Such is the case for sorption of pesticides. Although some progress has been made in identifying sorption mechanisms, the complexity of sorption from solution on mixed colloids, such as soils and sediments, has precluded rigorous theoretical analysis of reaction energies. Thus most characterizations of pesticide sorption on soils are empirical in nature. Simplified mathematical descriptions of sorption constitute only a minor sacrifice in the content of information on mechanisms of sorption. (The term "sorption" is used in this paper rather than "adsorption" because the former term includes both surface reactions and other types of chemical partitioning between the soil solution and hydrophobic components of soil organic matter.)

The most attractive simplification is that which can utilize existing or easily developed data on pesticides and soils or sediments to provide sorption estimates with the minimum loss of accuracy. Currently, the approach which is most widely accepted is a linear approximation of the sorbed-concentration/solution-concentration relationship, and expression of sorbed concentration with reference to organic carbon content rather than to the mass of the whole soil or sediment (see, for example, Hamaker and Thompson 1972, Chiou et al. 1979, Rao and Davidson 1980, Karickhoff 1981, McCall et al. 1981). An alternative approach is to express sorption on a surface area basis rather than on the mass basis (Pionke and DeAngelis 1980). The organic carbon basis is likely to gain the most acceptance because organic carbon content is commonly measured in soils and sediments, in contrast to surface area which must be estimated from other properties. Both alternatives are to be available in the SWAM model (Pionke et al. this volume).

The objective of this brief paper is to review the assumptions inherent in organic-carbon-referenced sorption of pesticides (K_{oc} approach) and to define the consequences when the assumptions are invalid. In addition. alternative methods of estimating a pesticide partition coefficient (K_{oc}) are discussed.

ASSUMPTIONS IN K_{oc} METHOD AND CONSEQUENCES

The principal assumptions are (1) equilibrium in the sorption-desorption process, (2) linearity of the sorption isotherm, (3) singularity of the isotherm for sorption and desorption (that is, sorption is reversible), and (4) sorption is limited to the organic component of the soil or sediment. Using the notation of Pionke et al. (this volume), the assumed relationship between sorbed concentration C_s (mg pesticide per kg dry soil or sediment) and the solution concentration C_{sol} (mg pesticide per L solution) is

$$C_s = K_d C_{sol} \qquad (1)$$

where K_d is the pesticide sorption distribution coefficient having units of L/kg. Whereas C_s represents pesticide sorption per unit mass of dry soil or sediment, C_s can also be adjusted to represent the amount of pesticide sorbed per mass of organic carbon:

$$C_s^{oc} = K_{oc} C_{sol} \qquad (2)$$

with K_{oc} also having units of L/kg when the mass of organic carbon is expressed in kilograms. If oc = (mass organic carbon)/(mass dry soil or sediment), K_{oc} is given by $K_{oc} = K_d/oc$, and $C_s^{oc} = C_s/oc$. Thus, equation 2 represents a linear sorption isotherm which is referenced to organic carbon content, and K_{oc} is essentially a partition coefficient which describes the partition of a pesticide between the aqueous phase and the soil organic phase. This approach is appropriate for hydrophobic, non-ionic pesticides with a water solubility of less than about 10^{-3} molar (Karickhoff 1981). Each of the assumptions inherent in the use of equation 2 to describe sorption in environmental assessments is discussed briefly.

Assumption of Equilibrium

Although there are a variety of laboratory methods available to measure sorption from

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solution (Green et al. 1980), the method used most commonly is batch equilibration, in which a known mass of soil or sediment is equilibrated with an aqueous pesticide solution of known initial concentration until equilibrium in the sorption process is achieved. The pesticide concentration in the aqueous phase is subsequently measured, and sorption is calculated from the change in pesticide concentration in solution. It is doubtful that true equilibrium is reached in a few hours for sorbents high in organic carbon, especially if sorption is relatively high. Karickhoff (1981) suggests that the sorption process has a rapid component and a slower component, the rate of the latter depending largely on movement of solute to less-accessible sorption sites; his analysis on one sediment indicated that the rate coefficient for the slow component varied inversely as the sorption partition coefficient.

For most practical applications laboratory measurements probably produce sorption coefficients which represent macroscale equilibrium quite well, even though equilibrium may not be reached at internal sorbent surfaces. The question to be answered, then, is whether or not "equilibrium" sorption coefficients measured in the laboratory can be used in pesticide transport models to represent partition of the pesticide between the aqueous and sorbed states. This question is difficult to answer in a general sense because field systems being simulated may or may not be near equilibrium. In near-static soil-water systems, such as a soil profile at field capacity without evapotranspiration, equilibrium is likely approached, and an equilibrium sorption coefficient may provide a good estimate of pesticide partition in the soil; laboratory results of Green and Obien (1969) for equilibration of atrazine in pots of soil at various water contents encourage such a conclusion. On the other hand, during infiltration and redistribution of water in soils, the equilibrium sorption coefficient appears to over-predict pesticide retardation in both laboratory columns and the field. Bilkert and Rao (1983) found that the equilibrium K_d of equation 1 had to be multiplied by a factor of about 0.4 to successfully predict the position of a pesticide peak in soil columns or in a field soil profile. This result is in general agreement with Rao and Davidson's (1980) conclusion, based on an extensive literature search of pesticide sorption data, that 40 to 60 percent of sorption is essentially instantaneous (less than one minute contact time). Assuming equilibrium conditions for dynamic systems will result in calculating too much pesticide in the sorbed state for the sorption process and too little in the sorbed state for the desorption process. Pionke et al. (this volume) present a rationale for treating the chemical system in the SWAM model as an equilibrium system. Perhaps acceptance of the equilibrium assumption should be considered a useful first approximation until the dynamics of detailed processes and their interaction are better understood and mathematically described.

Assumption of Linearity

The linear relationship (equations 1 and 2) is a desirable simplification for models as it allows simpler mathematical solutions. For many environmental contexts, for example runoff and stream flow, the linear approximation is probably quite accurate. Karickhoff (1984) cites evidence that for hydrophobic compounds sorbed on natural sediments the sorption isotherms are linear if the equilibrium concentration of solute in the aqueous phase is below 10^{-5} molar (1 to 3 mg/L) or less than one-half the solute solubility in water, whichever is lower. At the higher concentrations encountered in surface soils soon after a soil application of a pesticide, the linear assumption may result in sorption estimates that are in error by twofold to threefold or even more, depending on the extent of isotherm nonlinearity and the concentration of solute in solution. In an analysis of data from the literature for a large spectrum of organic compounds and numerous sorbents, Rao and Davidson (1980) found the exponent N in the Freundlich equation $S = K_f C^N$ to have a mean value of 0.87, with a coefficient of variation of 14.8 percent. These data included measurements made with solution concentrations far above the 10^{-5} M limit mentioned previously, but the results emphasize the difficulty of using a single sorption coefficient for a given chemical in all model applications. The error which results from assuming a linear relationship when the Freundlich equation (a power function) is actually appropriate was given in tabular form by Hamaker and Thompson (1972) and in graphical form by Rao and Davidson (1980).

Assumption of Singularity

An additional uncertainty in the measurement and application of sorption data is the question of whether a single sorption isotherm can represent both sorption and desorption of the pesticide. Numerous investigators have presented data showing a larger quantity of organic solute associated with the colloid for the desorption cycle than for the initial sorption measurement. This apparent nonsingularity, often called sorption hysteresis, has been assessed experimentally and from the literature by Rao and Davidson (1980); they conclude "that while nonsingularity of pesticide sorption-desorption isotherms may often be an artifact, it could be real and significant for certain compounds". Calculation of the error introduced by assuming singularity of a nonsingular Freundlich isotherm showed that the error is greater at low solution concentrations (that is, far away from the maximum solution concentration at which desorption was initiated) and decreases with increasing nonlinearity of the isotherm (Rao and Davidson 1980). The extent of hysteresis is apparently different for different particle size fractions. For example, Rao and Nkedi-Kizza (1983) have shown that diuron herbicide sorption on the clay-size fraction exhibited no hysteresis, while the sorption-desorption

isotherms for coarse silt and sand fractions were nonsingular. This finding is important because it is the finer size fractions that are predominant in runoff sediment. Thus, the error associated with the singular isotherm assumption may be acceptable for a comprehensive environmental model, but the impact should be evaluated by sensitivity analysis.

Assumption of Partitioning on Organic Carbon

The three assumptions above are inherent in the use of equation 1. Adoption of equation 2 as a further simplification is attended by some additional assumptions, which if invalid will introduce more error. It appears that the errors associated with the assumption of partitioning of pesticides on organic carbon may be much larger than those resulting from the first three assumptions. An awareness of the limits of applicability of the partitioning assumption is necessary if the model user is to avoid unacceptably large errors which may lead to inappropriate conclusions from model calculations.

If equation 2 were to be strictly correct and universal in its application, even if only among so-called hydrophobic organic pollutants, the following assumptions would have to be valid: (1) sorption occurs only on the organic component of the soil, that is, the mineral component has little or no effect; (2) the organic matter in all soils and sediments is the same with respect to its performance as a sorbent for a given hydrophobic organic solute; (3) the effect of variations in other factors, such as ionic strength of the solution, pH, and temperature, have little or no impact on the amount of pesticide sorbed.

Clearly, none of these assumptions are valid in the strict sense; hence, use of organic carbon-referenced sorption will introduce errors, the magnitude of which depend on how severely the assumptions are violated in a given system. Opinions concerning the K_{oc} approach for environmental assessments range from enthusiastic support (Chiou et al. 1979) to skepticism (Mingelgrin and Gerstl 1983). The application of this concept has been proposed and also questioned repeatedly since its introduction relative to pesticides in the early 1960's. Acceptance of the approach has been encouraged by the increasing need for calculation procedures applicable to hundreds of organic chemicals in hazard assessments for a wide range of environmental conditions. The importance and urgency of developing a generalized procedure justifies some sacrifice in scientific rigor and accuracy. On the other hand, theoretical justification for the K_{oc} approach has been provided by Karickhoff (1981, 1984), who identifies the organic-carbon/hydrophobic-chemical interaction as a first-order effect in contrast to the second-order effects of other factors of lesser importance. In practice, one must know when second-order effects are important. For example, Mingelgrin and Gerstl (1983) challenge the use of the partitioning concept (that is, that hydrophobic organic chemicals are partitioned between water and the organic component of soils or sediments in a manner analogous to partitioning between two immiscible solvents); they contend that other mechanisms may play a dominant role, for example, pesticide-clay-water interactions. These authors illustrate their point by showing the variability in K_{om} (sorption coefficient referenced to organic matter rather than organic carbon) for 12 compounds sorbed on soils or sediments having a wide range of organic matter contents. The largest variation in K_{om} was for parathion (factor of 50 between the largest and smallest value) and the smallest was for dieldrin (factor of 3). The variability that one might anticipate in K_{oc} values for a given compound is indicated by the coefficient of variability calculated for 43 chemicals by Rao and Davidson (1980).

The role of clay minerals in sorption of organic chemicals is addressed quantitatively by Karickhoff (1984). His analysis of a few sets of experimental data suggests that swelling clays may have important effects on sorption of some hydrophobic organics in sediments having low organic carbon contents, but when the ratio of clay mineral to organic carbon is less than 30, mineral contributions are masked regardless of the clay mineral content. Thus, further scrutiny of the available data and continued research in this area will help to define applications in which the K_{oc} approach is acceptable.

METHODS OF ESTIMATING SORPTION COEFFICIENTS

The following brief discussion relates to determination of K_d or K_{oc} when equations 1 and 2 are considered adequate for the modeling objective. Several methods of measuring and/or estimating sorption coefficients have been presented in detail in some recent publications (Lyman 1982b, McCall et al. 1981, Pionke and DeAngelis 1980, Green et al. 1980). In addition, useful compilations of pesticide sorption coefficients are provided by Pionke and DeAngelis (1980), Rao and Davidson (1980), and Hamaker and Thompson (1972). The options presently available to a potential user of the CREAMS and SWAM models are (1) Use reliable published K_{oc} values for the pesticides of interest. (2) Determine the required K_{oc} values by measuring K_d values on soils and/or sediments which are similar to those in the area of principal application and for which organic carbon values are known or can be measured; calculate $K_{oc} = K_d/oc$ for each soil or sediment sample, then obtain the average K_{oc} value. The variability in K_{oc} obtained on several samples will provide an indication of the reliability of the average K_{oc} for model application. (3) Calculate K_{oc} for each pesticide from the octanol-water partition coefficient (K_{ow}) using the log K_{oc} vs. log K_{ow} regression equation which is most appropriate for each pesticide. The K_{oc} vs. K_{ow} relationship has been shown to be surprisingly consistent for a wide range of soils and chemicals (Briggs 1981). Lyman (1982b) has tabulated six equations from

various sources; the tabulation includes the number of chemicals associated with each regression, the correlation coefficient, and the chemical class represented. Karickhoff (1984) discusses factors which contribute to variability in the K_{OC} vs. K_{OW} relationship. (4) If K_{OW} values are not available, it is possible to estimate K_{OW} (a) from chemical structure using fragment constants or (b) from other solvent/water partition coefficients. These methods are described in detail by Lyman (1982a). K_{OW} values estimated by these indirect methods can then be used to calculate K_{OC} in the manner described above.

In conclusion, K_{OC} values obtained from sorption measurements on soils and sediments from the region for which predictions are to be made will be the most accurate. Prediction of K_{OC} from K_{OW} is likely to introduce additional error and should be made with care, especially for soils or sediments with low organic carbon contents and high swelling clay contents. Predictions based on molecular fragments are probably the least reliable presently, but provide a rough first approximation when no alternative exists. Irrespective of the method used to estimate K_{OC}, the probable errors of estimation should be identified and the acceptability of the method evaluated by a parameter-sensitivity analysis with the environmental model of interest.

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PESTICIDES IN SURFACE IRRIGATION RUNOFF WATER

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INTRODUCTION

Agriculture has received considerable blame for the presence of pesticides in surface and ground waters. One of the pathways by which pesticides leave treated fields is in runoff water. Many investigators have reported pesticide losses in runoff from rainfall (Caro 1976; Wauchope 1978; Willis and McDowell 1982). Several models, including CREAMS (Knisel 1980) and CREAMS II, have been developed for estimating amounts of pesticides in surface runoff from rainfed agriculture. Very little published data are available on pesticides in runoff from irrigated fields in spite of the fact that the Western States account for almost half of the Nation's total consumption of pesticides. Most of these are applied to irrigated alluvial soils. We need to develop capabilities for predicting amounts of pesticides in runoff from irrigated fields.

A 4-year study was just completed to measure concentrations of pesticides in irrigation runoff water as influenced by pesticide characteristics, time, method of pesticide application, and irrigation practices on large farms in Imperial Valley, California (Spencer et al. 1984). The detailed data should be useful for developing and testing an operational irrigation-pesticide model to extrapolate the findings to other areas and other conditions. This paper presents the results of these studies on runoff of pesticides from irrigated fields, examines some of the processes affecting concentrations and amounts of pesticides in runoff water, and discusses some of the relationships which may be useful in developing modeling capabilities.

EXPERIMENTAL

Pesticides were determined in irrigation runoff water from fields planted to cotton, sugarbeets, alfalfa, lettuce, cantaloup, and onions over a 4-year period. The instrumentation for each field included propeller water meters for measuring incoming irrigation water, Parshall flumes for measuring outgoing runoff water, and slotted tubes on tile lines for measuring tile drainage water. Pesticide concentrations were measured periodically, and the total amounts of pesticides removed from the treated fields in runoff waters were calculated from flow volumes and pesticide concentrations.

The farmers determined the crops to be grown on the fields and pesticides to be applied.

Pesticides measured in the runoff water were insecticides or herbicides applied by aerial application or ground rig, or herbicides applied directly in irrigation water during the growth of the crop. Water samples were analyzed for a total of 20 pesticides (14 insecticides and 6 herbicides). Based on the relationship between pesticide concentration and the runoff hydrograph, we sampled runoff water most frequently during the first irrigation after a pesticide application. For the second irrigation, samples were taken at approximately half-hour intervals for the first 2 or 3 hours after start of runoff and then at 2- to 4-hour intervals. For subsequent irrigations, samples were taken four to six times per event. Before some irrigations, soil samples to a depth of 1 cm were collected from the irrigation furrow, or the area to be wetted, for the purpose of relating soil concentrations to pesticide runoff.

RESULTS

Table 1 provides a summary of total seasonal losses in irrigation runoff water for several pesticides. Each figure represents the runoff from several individual irrigations during the growth of the crop. The amounts of pesticides in runoff water varied considerably, depending upon the pesticide, its method of application, and the irrigation runoff water volume or irrigation efficiency. The percentages of the applied pesticides lost in runoff were generally very low with the exception of 1) EPTC applied directly in irrigation water, 2) insecticides applied by air while irrigation water was on the field, and 3) one herbicide, prometryn, applied at midseason to cotton as a directed spray to the furrow and bed surfaces.

Runoff water was usually equal to about 15 to 20 percent of the applied irrigation water. In general, higher runoff rates occurred with soil-applied herbicides than with aerially applied insecticides, and the herbicides persisted longer than did the insecticides. Concentrations were highest in the first irrigation following pesticide application, and the time elapsed between application and the first irrigation was inversely related to concentrations of pesticides in the runoff water. Data were collected for more than 300 individual pesticide/irrigation runoff events. Data in table 1 are useful in making general comparisons between pesticides, but an examination of data from the individual irrigation events is necessary to evaluate water quality effects and to determine the soil, crop, or water management practices that influence amounts of pesticides in irrigation runoff water.

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Table 1.--Seasonal losses of selected pesticides in irrigation runoff in Imperial Valley, California[1/]

Pesticide	Year	Crop	Total amt applied kg/ha	Pesticides in runoff Total amt g/ha	% of total applied
Herbicides					
DCPA	1980	Cotton	7.6	92.6	1.22
"	1981	Cotton	3.4	47.7	1.40
"	1981	Cotton	3.6	49.2	1.37
Prometryn	1979	Cotton	3.1	157	5.0
"	1980	Cotton	1.6	23.5	1.5
"	1981	Cotton	1.6	27.2	1.7
"	1980	Cotton	1.3	12.4	0.95
Trifluralin	1981	Cotton	1.1	3.21	0.29
"	1980	Cotton	0.96	1.38	0.14
Insecticides					
Methidathion	1980	Cotton	1.12	2.3	0.21
"	1978	Cotton	1.12	1.76	0.16
"	1979	Cotton	1.02	20.5	[2/] 2.0
E. Parathion	1981	Lettuce	0.83	0.18	0.02
"	1980	Lettuce	4.20	18.4	0.44
"	1978	Sugarbeets	1.11	5.71	0.51
"	1979	Sugarbeets	2.07	6.52	0.31
"	1979	Sugarbeets	2.51	8.50	0.34
"	1980	Alfalfa	0.28	0.18	0.06
M. Parathion	1981	Lettuce	0.42	0.013	0.003
"	1980	Lettuce	2.1	6.70	0.32
"	1978	Sugarbeets	0.56	1.71	0.31
"	1979	Sugarbeets	1.02	1.67	0.16
"	1979	Sugarbeets	1.25	2.10	0.17
"	1980	Alfalfa	0.14	0.02	0.01
Methomyl	1980	Cotton	0.4	6.9	1.73
"	1981	Lettuce	3.41	16.3	0.48
"	1980	Lettuce	3.16	21.1	0.67
"	1978	Sugarbeets	3.49	8.78	0.25
"	1979	Sugarbeets	4.01	11.7	0.29
"	1981	Alfalfa	1.93	5.3	0.27
"	1979	Sugarbeets	5.82	20.4	0.35
"	1980	Alfalfa	0.79	1.00	0.13
"	1980/81	Alfalfa	5.54	39.6	0.71

1/ Each value represents the runoff from several individual irrigation events during the growth of the crop.

2/ 99% of the total Methidathion loss occurred following an aerial application during irrigation.

The relationships between pesticides in runoff and several independent variables were determined by linear regression analysis. The amounts of sediment in runoff, the runoff water volume, and the accumulative water applied since the last pesticide application were not highly correlated with amounts of pesticides in runoff. Amounts and concentrations of pesticides in runoff were most highly correlated with the time elapsed since the last pesticide application and with the soil pesticide content.

Time elapsed between pesticide application and the irrigation event was inversely related to log pesticide concentration, indicating a first-order rate of decrease in runoff concentration with time. An example of the relationship between log concentration and time is illustrated in figure 1 with data on ethyl and methyl parathion for all crops and irrigations. The linear regression model indicated a correlation coefficient, r, of -0.872 and -0.932, with half lives of 12 and 7.7 days for ethyl and methyl parathion,

respectively. This is a half-life for the runoff water concentration decrease and not soil persistence. The regression curve can also be used to estimate the runoff concentration expected at time 0, that is, 7.7 and 3.9 µg/L for ethyl and methyl parathion.

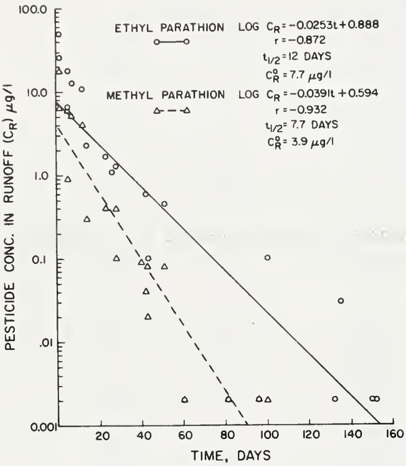

Figure 1.--Relationship between concentrations of ethyl and methyl parathion and time elapsed since the last pesticide application for all fields and all irrigations.

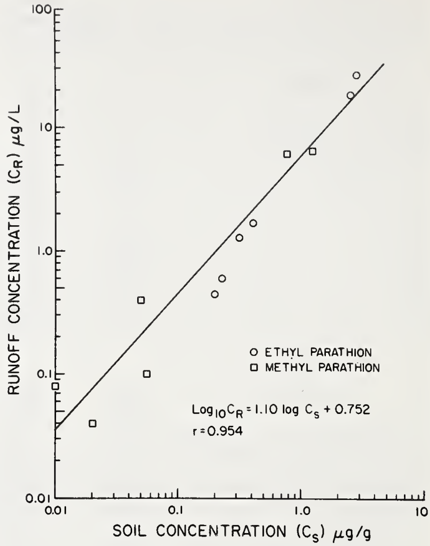

Figure 2.--Relationship between concentrations of ethyl and methyl parathion in runoff water and concentrations in the surface soil (0-1 cm).

Even when all irrigations were combined, the linear model for log concentration versus time fit the data quite well for most of the herbicides and for other pesticides on individual crops. Correlation coefficients were generally decreased when groups of chemicals were combined, such as, all herbicides, insecticides, or any subgroups within the insecticides.

The concentrations and amounts of pesticides in the 0- to 1-cm depth of soil proved to be good indicators of the concentrations and amounts of pesticides to be expected in runoff water. A highly significant correlation between concentrations of pesticides in runoff water was observed for most of the pesticides and pesticide groups, with the exception of the pyrethroids and organochlorine insecticides. For example, figure 2 shows log concentration in runoff versus log soil concentration for ethyl and methyl parathion with r equal to 0.954, even when data for both pesticides were combined. Similarly, correlation coefficients relating log runoff concentration to log soil concentration were 0.845, 0.920, and 0.940 for prometryn, DCPA, and methomyl, respectively.

The relationship between time and changes in pesticide concentration in the surface soil is also an important predictive parameter for modeling purposes. Simple linear regressions relating time since the last pesticide application to log concentrations or log amounts of pesticides in the 0- to 1-cm depth of soil were used to calculate degradation constants for pesticides in the soil. With most pesticides, the decrease in concentration followed a first-order rate, with highly significant correlations between time and log concentration or log amount remaining in the soil. To illustrate, figure 3 shows the relationship between time elapsed since the last application and log concentration of ethyl and methyl parathion in the 0- to 1-cm soil depth. Correlation coefficients of -0.771 and -0.908 with $t_{1/2}$ of 13 and 7.8 days were observed for ethyl and methyl parathion, respectively. Degradation constants or $t_{1/2}$ includes all routes of dissipation from 0- to 1-cm depth of soil such as volatilization, leaching, and degradation by biological or chemical means. Similar relationships were observed with other individual pesticides for which sufficient soil data were obtained. The data should be useful for developing predictive capabilities for estimating pesticides remaining in the soil and, consequently, concentrations or amounts in runoff.

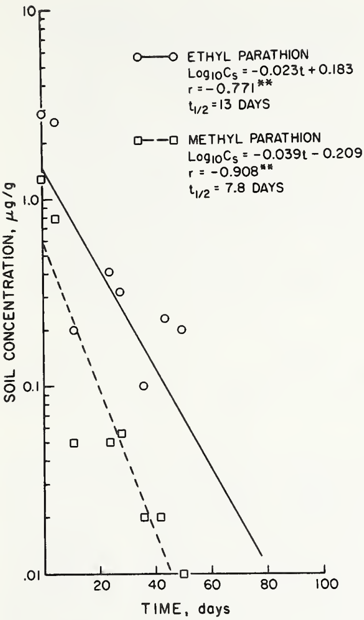

Figure 3.--Relationship between concentrations of ethyl and methyl parathion in the surface soil (0-1 cm) and time elapsed since the last pesticide application.

None of the pesticides were identified in tile drain effluents at concentrations above minimum detectable levels of 1-2 p/t in 30-liter tile drain water samples extracted on XAD-2 resins. This indicates that most of the presently used pesticides are not sufficiently persistent, or they are not sufficiently mobile to reach groundwater in the relatively heavy soils in the Imperial Valley.

SUMMARY AND CONCLUSIONS

Pesticide concentrations were determined in samples of surface irrigation runoff water following the application of 20 pesticides to large fields of cotton, sugarbeets, alfalfa, lettuce, onions, or cantaloups in Imperial Valley, California. Except for the pyrethroids, most of the pesticides were transported in the water phase.

Time elapsed between pesticide application and the irrigation event was inversely related to log concentration, indicating an approximate first-order rate of decrease in runoff concentration with time. Pesticides in the 0- to 1-cm depth of soil proved to be good indicators of the concentrations and amounts of pesticides to be expected in runoff water under furrow irrigation systems used in Imperial Valley. The amounts of sediment in runoff water, the runoff water volume, and the accumulative water applied were not highly correlated with amounts of pesticides in runoff.

The detailed data from this runoff study (Spencer et al. 1984) and the observed relationships between runoff concentration, time, and soil pesticide concentration, along with soil persistence curves, will be useful data bases for developing and testing models to estimate pesticide concentrations in runoff water from other irrigated areas. Consequently, a logical followup to this work is the development of an operational irrigation-pesticide model for estimating pesticide runoff from irrigated fields. This will require joint efforts of soil scientists and hydrologists in coupling a pesticide submodel with a hydrologic submodel for furrow or border irrigation, and someone to test the model using available data.

The pesticide submodel used in CREAMS (Knisel 1980) may be a useful starting point in developing a submodel routine for surface irrigated fields since many routes of dissipation from the soil, such as volatilization, leaching, and degradation are similar in irrigated and rainfall areas. However, washoff of pesticides from foliage to soil and the raindrop impact will not be important in mobilizing pesticides at the soil surface in most irrigated fields. The detail with which pesticide runoff could be simulated might include the runoff hydrograph and the pesticide flux with time during a runoff event, or merely total runoff per irrigation event similar to the detail being simulated by CREAMS in rainfall areas.

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NITROGEN-CYCLING MODELS

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INTRODUCTION

Nitrogen is a major nutrient in all ecosystems within the biosphere. The total nitrogen in the components within ecosystems may be thought of as its nitrogen capital. This nitrogen capital is in a dynamic state, moving from one component to another as it serves as substrate or end product for biological, chemical, and physical reactions. The nitrogen compounds may react with hydrogen and oxygen and are transported as biological products (for example, meat, corn, wheat) or gas- or water-soluble compounds. The amount of time a nitrogen atom resides in a component or compound may range from a few minutes to thousands of years. However, in each ecosystem, certain chemical and biological reactions and transports occur under the control of the abiotic environment and complex of biological organisms in that environment.

A major objective of ecosystem science is to determine the biological and chemical nitrogen transformations occurring in various ecosystems, to what extent the ecosystems are similar, and in what ways they are unique or dissimilar. With such information, scientists have sought to find ways they might manage the nitrogen capital of ecosystems, especially agroecosystems, including forests. In the early conceptualizations of the behavior of nitrogen, scientists studied processes (for example, nitrogen fixation, assimilation, immobilization, mineralization, nitrification, denitrification), and such processes have been described in many publications, of which only a few can be cited here (Harmsen and Van Schreven 1955, McElroy and Glass 1956, Jansson 1958, Alexander 1961, Bartholomew and Clark 1965, Campbell and Lees 1967, Allison 1972, Nielsen and MacDonald 1978, Hewitt and Cutting 1979, Stevenson 1982). Numerous diagrams have been published showing various ways these processes may be linked together, and this literature has led to the concept of a nitrogen cycle. However, one must be careful not to fall into the trap that such diagrams describe pathways strictly followed in every system. Many scientists have attempted to draw up nitrogen balance sheets for the nitrogen capital in various ecosystems, but the attempts have met with only mediocre success (Allison 1955).

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With the advent of the computer, scientists have been able to construct flow diagrams or models to show the input, flow through, and output of various nitrogen components in ecosystems. Recent review articles by Frissel and Van Veen (1982), Tanje (1982), and Hunt and Parton (1984) give an overview of existing nitrogen-cycling models. The book edited by Frissel and Van Veen (1981) is also very useful, since it describes 15 nitrogen-cycling models and compares the way different nitrogen-cycling processes are represented. They suggest that a good method for classifying models is according to the processes emphaized by the models. The major nitrogen-cycling processes generally represented are volatilization of ammonium, mineralization, immobilization, nitrification, denitrification, ammonification, and uptake by the roots.

The major purpose of this paper is to compare and contrast the nitrogen-cycling models of McGill et al. (1981), Reuss and Innis (1977), and Parton et al. (1983). We will show that the objectives for developing the models greatly influence the structure of the models. The McGill et al. (1981) model (PHOENIX) is process oriented and designed to advance our scientific understanding of nitrogen cycling in grassland soils. The Reuss and Innis (1977) model is also process oriented but was intended to be used for a variety of grassland sites. Thus, it has a simpler structure and is easier to adapt to other sites. The Parton et al. (1982) model for soil organic matter is the simplest and most management oriented of the three models and was designed to simulate the long-term effect of various agricultural practices on soil organic matter levels, nitrogen cycling, and plant production.

Gold (1977) discusses the difference between correlative and explanatory models. Explanatory models are structured to be analogous to real systems and thus to embody the hypotheses advanced about how the real system operates, while correlative models (for example, regression models) are not constrained by the mechanisms operating in a real system. The model presented in this paper falls along the continuum between explanatory and correlative models, with PHOENIX as the most explanatory and the models of Reuss and Innis (1977) and Parton et al. (1983) more correlative and less explanatory. The comparison of the models will demonstrate that, as the objective of a model becomes more applied, the structure of the model becomes generally less mechanistic and simpler. We will also show that the different ways used to represent microbes in nitrogen models is one of the most important differences among models.

Model Comparisons

The PHOENIX nitrogen model (fig. 1) is a good example of an explanatory model; the stated objective is "to explain . . . the relation-

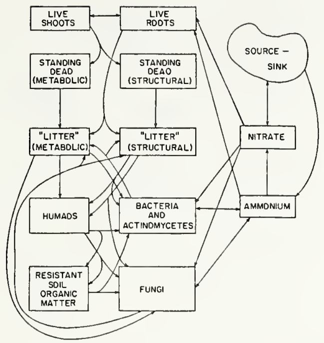

Fig. 1.--PHOENIX N-flow diagram (McGill et al. 1981).

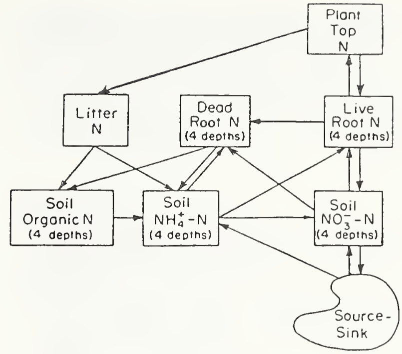

Fig. 2.--Flow diagram for nitrogen flow in a grassland ecosystem (Reuss and Innis 1977).

ships between plant processes and microbial processes and the effect on plant production, microbial secondary production and nitrogen cycling" (McGill et al. 1981). The carbon- and nitrogen-flow models have the same structure, except for the inorganic nitrogen compartments. PHOENIX has a number of distinctive features, including separating plant residue into a structural and metabolic components, dividing soil organic matter into humads and resistant soil organic matter, and representing the dynamics of bacteria and fungi separately. The structural component consists of cell walls, and the metabolic component includes the nucleus and vacuole and cytoplasm.

The term humad "designates materials . . . believed to be of a diverse, heterogeneous chemical nature which are stabilized by humification and adsorption" (McGill et al. 1981) and includes material formed by adsorption of metabolic material onto existing humads and release of material resulting from the decomposition of structural material (for example, phenolics). Microbes decompose humads, and a small fraction of decomposed humads are transformed into resistant organic matter with a long turnover time (500 to 1,000 yr). The dynamics of bacteria and fungi are represented in the model and include such processes as death, growth, uptake of nitrate and ammonium, and mineralization. Uptake of inorganic N is a function of the solution concentration of inorganic N and the microbial demand for N, which is controlled by the C:N ratio of the microbes. Fungi and bacteria have different C:N ratios and responses to temperature, water, and substrate quality and quantity.

The major advantage of process-oriented mechanistic models (for example, PHOENIX) is that they are more likely to respond correctly to a great diversity of perturbations, such as different cultivation practices, fertilization, irrigation, and fire. The disadvantages generally include the increased computer time, greater difficulty in adapting the model to other sites, validation of the model, and a larger number of required data inputs. Validation of PHOENIX is particularly difficult because many of the state variables included in the model are difficult, if not impossible, to measure in the field. For example, it is difficult to measure bacterial and fungal biomass in the field, and the data are generally not available for most sites.

The Reuss and Innis (1977) nitrogen-cycling model (fig. 2) was developed to apply to a variety of grassland types and was part of a total-ecosystem grassland model (Innis 1978). The model is less complex than PHOENIX and uses a less mechanistic approach to represent processes. The state variables in the Reuss and Innis (1977) model are shown in figure 2. The processes represented by the model include plant uptake; translocation between live roots and shoots; decomposition of surface litter, dead roots, and soil organic nitrogen; formation of soil organic matter; mineralization and immobilization of nitrogen; and nitrification.

All decomposition and N-transformation flows are controlled by soil temperature and water. Uptake of nitrate and ammonium by roots are functions of the solution concentrations of nitrate and ammonium, according to a Michaelis-Menten equation. Translocation of nitrogen between roots and shoots is controlled by the ratio of live top and live root nitrogen concentrations, and it varies as a function of the phenological state of the plant. Mineralization of N from decomposing litter and dead roots is a function of N content of the material and decreases to zero at N concentration <1 percent. Nitrogen is immobilized by dead roots at a rate that decreases as the root-N concentration

increases to 2.5 percent. The structure of the Reuss and Innis (1977) model is less complex than that of PHOENIX, since it has only one soil organic matter compartment and microbes are not explicitly represented (they are grouped with dead roots and litter). The effect of microbes on N flow is included in the other flows. For example, N-immobilization flow to dead roots represents uptake of inorganic N by microbes in dead roots.

One of the major advantages of the Reuss and Innis model is that state variables correspond to variables that are easily measured in the field; thus, the model can be easily adapted to a given site and validated. A disadvantage of the model is that the simple structure can make it difficult to correctly represent the effect of management practices or experimental manipulation, such as fumigation of microbes. For example, Risser and Parton (1982) found that the Reuss and Innis model overestimated the negative effect of annual fire on tallgrass prairie. This was a result of the model's structure, which does not allow mineral N to be immobilized by surface litter. The detailed structure of PHOENIX, however, makes representing experimental manipulation and management practices much easier. For example, the validation of output section in the paper of McGill et al. (1981) shows that PHOENIX qualitatively predicts the response to fertilization, soil fumigation, organic residue amendments, and cultivation.

Soil Organic Matter Model

Parton et al. (1983) developed a model to simulate the effect of different cultivation practices on levels of soil organic matter and crop yields. The model was designed to simulate changes over long periods of time (100 to 1,000 yr) and thus has a fairly simple structure compared with other models that are too expensive to run for such long periods. The nitrogen-flow diagram (fig. 3) shows three soil organic matter fractions: (1) an active fraction containing live and dead microbes (~3-yr turnover time), (2) a fraction physically protected and/or chemically resistant to decomposition (20- to 30-yr turnover time), and (3) a recalcitrant fraction with a long turnover time (1,000 yr). The model assumes that the C:N ratios remain fixed at 80, 5, 8, 10, and 11, respectively, for the structural, metabolic, active, slow, and passive soil organic fractions. Plant residues are divided into structural and metabolic components as a function of the C:N ratio of the plant residue (as in PHOENIX). Most of the processes are a function of soil temperature and moisture. Nitrogen-flow rate is equal to the product of carbon-flow rate and the fixed N:C ratio of the variable receiving the material. The N attached to carbon lost in microbial respiration (60 to 80 percent of C) is assumed to be mineralized. Decomposition of metabolic residue and active, slow, and passive soil organic

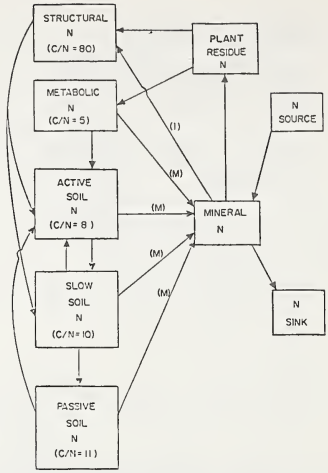

Fig. 3--Simplified N-cycling flow diagram for soil organic matter dynamics (Parton et al. 1983).

matter results in net N mineralization, while decomposition of structural residue (high C:N ratio) results in immobilization of N. In the model, we assume that microbes control all decomposition flows and that the efficiency of microbial production is 40 percent for decomposition of structural residue and the soil organic fraction and 20 percent for metabolic residue.

A long-term field experiment in Sweden was used to test the model's ability to predict change in crop yield and soil organic matter levels (see fig. 4). The five treatments modeled were (1) a fallow treatment (no cropping), (2) a control (cropping with no addition of aboveground C and N), (3) a nitrogen treatment (cropping with N fertilization), (4) a straw treatment (cropping with incorporation of straw into the soil), and (5) an N-plus-straw treatment. The four cropping treatments were planted annually, and 97 percent of aboveground plant material was removed from the site.

Results of model output and observed soil organic matter (SOM) and crop yields compared very favorably. The straw treatment had the highest SOM, followed by the straw, nitrogen, control, and fallow treatments. Plant production was highest in the N-plus-straw treatment, followed by the nitrogen, control, and straw treatments. When the results are evaluated, it is important to note that the objectives of the model are to simulate long-term trends, not year-to-year variations caused by variations in the weather.

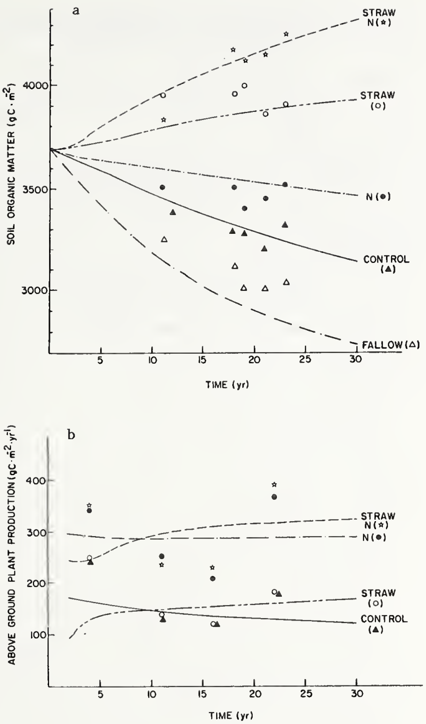

Fig. 4.--Simulated vs observed total soil organic matter (a) and plant production (b) for an experiment in Sweden (Parton et al. 1983)

SUMMARY

Comparison of the three models shows their relative advantages and disadvantages. One of the main advantages of simple models is that they are relatively easy to validate, since the criteria for validation are generally less stringent and the types of data needed by the models are more available. The complex process-oriented models are more difficult to validate because they generally have a larger number of state variables and require data that are difficult to observe in the field (for example, time series of microbial biomass) and available from few sites. The advantage of complex models is that they are more likely to respond correctly to a large number of perturbations because they include more of the factors that influence the processes included in the models. For example, including live microbial biomass in PHOENIX allows the model to respond to management practices that manipulate microbial biomass. The model comparisons show that model structures can be represented in different ways, depending on the objectives of the models. The major structural differences are the ways microbes are represented and how they influence the flow of nitrogen.

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MODELING OF MICROBIAL ACTIVITY: MINERALIZATION, IMMOBILIZATION, NITRIFICATION, AND DENITRIFICATION

W. H. Caskey and J. S. Schepers[1]

INTRODUCTION

Nitrogen cycling in the environment encompasses several forms of nitrogen, many possible animal and plant species, and a variety of microorganisms. Within the overall nitrogen cycle are smaller internal cycles, such as the N transformations that occur in the soil. These soil nitrogen transformations are largely the result of soil-borne microorganisms, and five major processes are involved: nitrogen fixation, mineralization, immobilization, nitrification, and denitrification. Nitrogen fixation by free-living microorganisms is generally considered to be insignificant with respect to the total nitrogen budget in agricultural soils, and symbiotic N fixation is limited to legume crops. Hence, N fixation will not be considered. The release of N as ammonium during the decomposition of organic matter is termed "mineralization" and is accomplished by a wide variety of microorganisms. This released ammonium can serve as a source of nitrogen for plant or microbial growth or it can be converted to nitrate by other soil bacteria. The utilization of the ammonium by the microflora with resultant incorporation of the N into the microbial biomass or into the soil organic matter is immobilization. Nitrification is the oxidation of ammonium to nitrate and is accomplished by autotrophic bacteria. Nitrification by heterotrophic microorganisms is of limited importance in soil. The nitrate may then be utilized by the plants or it may be denitrified if oxygen becomes limiting. Denitrification is the conversion of nitrate to nitrogenous gases (nitrous oxide and dinitrogen) under anaerobic conditions.

A variety of physical and chemical properties of the environment affect the growth and activity of microorganisms, and these same factors regulate the processes of N transformations in soils. A process level model of the soil environment must consider these microbial processes and their regulatory mechanisms. We will discuss the influence of the physical and chemical environment as related to the activity of N-transforming bacteria in the soil and present an example of how these interactions may be incorporated into a model using the example of denitrification.

ENVIRONMENTAL EFFECTS ON MICROBIAL ACTIVITY

Physical and chemical characteristics of the environment that influence the rates of microbial activity are moisture, oxygen supply, pH, temperature, nutrient supply, surface tension, and osmotic pressure. Of these, nutrient availability, aeration status (moisture and oxygen supply), and temperature are the most important. The physiological heterogeneity of the microorganisms involved in the cycling of nitrogen in the soil results in exerted effects specific to a particular process. For example, nitrification is an aerobic process and denitrification is an anaerobic process, whereas mineralization occurs under both aerobic and anaerobic conditions. And, even when the response is similar, the magnitude of the response varies.

Nutrient Supply

Heterotrophic microoganisms are largely responsible for mineralization, immobilization, and denitrification. Energy is required for activity, and the predominant source of this energy is readily available organic matter, either from residues or from root exudates. Therefore, two nutrients, readily decomposable carbon and the appropriate nitrogen species, exert an effect on the rate of nitrogen transformations by heterotrophic bacteria. For autotrophic bacteria, only the nitrogen species is important since carbon dioxide is rarely limiting in the soil atmosphere. The effect of substrates on pure cultures of bacteria and on enzymes isolated from these cells generally follow saturation-type kinetics as described by the Michaelis-Menten equation. The Michaelis-Menten equation describes a hyperbolic saturation and contains two parameters which can be used to effectively describe the process: maximum reaction rate and the Michaelis constant. In order to measure these parameters, the number of binding sites must remain constant and all other factors must be nonlimiting. The maximum reaction rate is the rate observed when the addition of substrate does not increase the rate of the reaction. The Michaelis constant is the substrate concentration at which the apparent rate of the reaction is one-half the maximal rate. This model has been applied to microbial activity in nature, with the Michaelis constant generally considered to be a measure of the relative effectiveness of a particular bacterial species to compete for the substrate under consideration (Wright and Hobbie 1966, Williams 1973, Burnison and Morita 1974). For the processes of mineralization and immobilization, the effect of C:N ratio is superimposed on the effect of concentration of carbon and nitrogen. The decomposition rate is a function of the nitrogen content of the substrate (Hunt 1977). Generally, a low C:N ratio of the material being decomposed will stimulate mineralization, while a high C:N stimulates immobilization. Parnas (1976) has suggested that the rates of mineralization and immobilization are a function of the C:N ratio of the substrate with respect to the optimum C:N ratio of the active decomposing population. Although soil microorganisms generally favor the readily available organic matter as an energy source, other carbonaceous material is decomposed. Some resistant forms of carbon are formed which remain in the soil and decompose at slower rates (Jenkinson and Rayner 1977). So, not only the amount of organic matter, but also the type, must be considered when examining the effect of carbon availability on heterotrophic processes in soil.

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The reduction of nitrate during denitrification by pure cultures of denitrifying bacteria appear to obey Michaelis-Menten kinetics (Betlach and Tiedje 1981). There is considerable disagreement about the order of the denitrification process with respect to nitrate in soil systems (Kirda et al. 1974, Starr et al. 1974, Starr and Parlange 1976, Bremner and Shaw 1958, Phillips et al. 1978, Reddy et al. 1978). Bowman and Focht (1974) concluded that denitrification rates are dependent on nitrate concentration according to Michaelis-Menten kinetics when the concentration was expressed on the basis of soil solution, thus resolving these discrepancies. Kohl et al. (1976) also reported that denitrification kinetics fit the Michaelis-Menten equation but indicated that the kinetics were equally well fit by exponential equations and the solution to a pair of nonlinear differential equations representing a system in which the product of one reaction is a substrate in a second sequence. The apparent Michaelis constants for pure cultures are 15 μM and lower (Betlach and Tiedje 1981). However, the values for soils are higher and highly variable (Table 1).

Table 1.--Apparent K_m values for nitrate reduction during denitrification in soils

Source	K_m
	- mM -
Kohl et al. (1976)	3.5
	0.29
Bowman and Focht (1974)	12.1
Klemedtsson et al. (1977)	0.23
Yoshinari et al. (1976)	0.13
	1.2

The electrons required to reduce the nitrogenous oxides during denitrification derive from the soil organic matter. As a result, the availability of organic matter is one of the most important factors regulating the rate of denitrification. The rate of denitrification in soils is stimulated by the addition of carbon as glucose, straw, and alfalfa (Bowman and Focht 1974, Nommik 1956, Wijler and Delwiche 1954) and denitrification rates have been shown to closely approximate Michaelis-Menten kinetics with respect to added gluclose (Bowman and Focht 1974). The denitrification potential of soils is correlated with total organic carbon, but more so with water-soluble organic carbon or mineralizable carbon (Burford and Bremner 1975). Stanford et al. (1975) observed similar correlations for total carbon and extractable glucose equivalent carbon in 30 soils of diverse origin. Burford and Bremner (1975) concluded that analysis of soils for mineralizable carbon or water-soluble carbon provided a good index of their capacity for denitrification. Molina et al. (1983) have used such an approach in NCSOIL in modeling denitrification. The base denitrification rate is calculated from the available organic matter pool, then modified by the other factors which exert regulatory effects on the process. Figure 1 illustrates the relationship between readily available organic matter (as water-soluble organic carbon and denitrification potential for 17 soils.

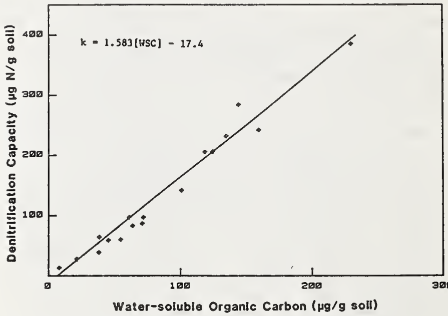

Figure 1.--Relationship between denitrification capacity and water-soluble organic carbon for 17 soils, from Burford and Bremner (1975).

Temperature

A maximum temperature and a minimum temperature delimit the activity of microorganisms, with these temperatures being a function of the general protein structure of the microorganism. Although the ranges of temperatures for microbial activity vary widely for specific organisms, the agriculturally significant activity occurs from about freezing to 35 or 40 °C. Within this range, microbial processes are assumed to double in reaction rate for each 10 °C increase in temperature, a Q_{10} of 2.0. For soil nitrogen transformations mediated by microorganisms, the Q_{10} has been reported to vary from 1.5 to 3.0 (Bailey and Beauchamp 1973, Nommik 1956, Stanford et al. 1973, Stanford et al. 1975).

The rate of denitrification in soils is dependent on temperature (Knowles 1982). The rate increases with temperature with an apparent optimum of 60 to 67 °C (Keeney et al. 1979, Broadbent and Clark 1965). However, Keeney et al. (1979) suggested that biological denitrification dominated below 50 °C, while above that temperature chemical denitrification also contributes significantly to nitrogen gas evolution. The apparent temperature optimum for biological denitrification in soils is 35 °C (Stanford et al. 1975). Generally, changes in the rate of microbial activity over this range can be described using the standard Arrhenius equation. Rickman et al. (1975) derived the temperature factor shown below and successfully used it to model dry matter accumulation in winter wheat.

$$T_f = e^{-x}$$

where $x = A^T(\frac{T_{opt}-T}{T})$

A = constant
T = Temperature (K)
T_{opt} = optimum temperature for growth (K)

This equation is of the same form as the derivative of the Arrhenius equation. Applying the data from Stanford et al. (1975) and assuming a temperature optimum of 35 °C, the value of A for denitrification is 1.0216.

pH

For most bacteria, the optimum pH for growth and activity is 6.5 to 7.5 and activity decreases as the hydrogen ion concentration deviates from this optimum. The optimum pH for bacteria is related to their metabolism, but pH changes in the environment may induce compensatory enzymatic changes in the microorganisms. The effect of pH on microbial activity may result indirectly by altering enzyme activity, the permeability of the cell, or solubility of chemicals. For example, complete oxidation of ammonium to nitrate occurs in a restricted range, the boundaries of which are difficult to ascertain in soils. The complexity results because the effect of pH is exerted through the toxic concentrations of free nitrous acid and free ammonia (Anthonisen et al. 1976) that occur at different pH.

Denitrifying bacteria are sensitive to low pH (Bollag et al. 1970, Valera and Alexander 1961), but the effect of pH on denitrifying activity in soil is less clear. Some workers (Bremner and Shaw 1958, Dubey and Fox 1974, Muller et al. 1980) have found a correlation between pH and denitrification rate. Others (Burford and Bremner 1975, Stanford et al. 1975, Koskinen and Keeney 1982) have observed no effect of pH on denitrifying activity in soils. Koskinen and Keeney (1982), using samples from the same soil type which had been maintained in the field at various pH levels, observed good correlation between denitrification capacities of the samples and water-soluble carbon concentrations and concluded that the rate of organic carbon mineralization rather than pH controlled the denitrification rate in these carbon-limited systems. Muller et al. (1980) observed a linear relationship between pH and denitrification rate (fig. 2) for a variety of soils, many of which were low pH, and this relationship probably is the best description of the relationship between pH and denitrification rate without considering the mechanism of the effect.

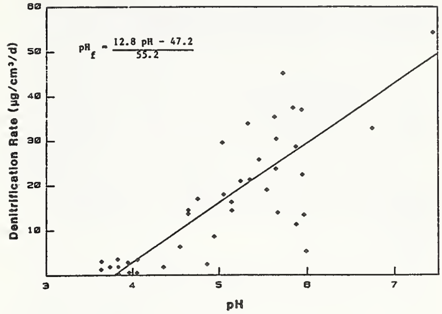

Figure 2.--Correlation between denitrification rate and soil pH from Muller et al. (1980). The pH_f was calculated from a regression equation, assuming an optimum pH of 8.0.

Moisture and Oxygen Supply

Moisture is required for microbial activity, and desiccation decreases that activity. But bacteria possess survivial mechanisms that allow them to survive such a stress, as evidenced by the occurrence of measurable microbial activity in soils which have been stored air-dried for several years. The greater effect of moisture on microbial activity is by regulating the oxygen availability in soil. Aerobic microbial activity generally increases as the soil moisture content increases until aeration becomes limiting, which occurs when approximately 60 percent of the soil pores are filled with water (Greaves and Carter 1920). Linn and Doran (1983) have used percent water-filled pore space (%WFP) to describe the effect of aeration on microbial activity and suggested that the changeover from aerobic to anaerobic metabolism occurs at 60 percent WFP (fig. 3). Aulakh et al. (1982) have observed that soil %WFP must be greater than 50 percent for denitrification rates to increase. Percent water-filled pore space is a simple concept which can be calculated from soil

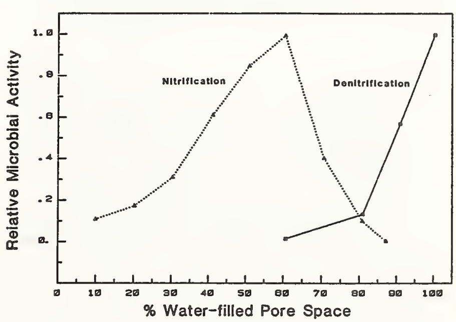

Figure 3.--Relationship between percent water-filled pore space and microbial activity, from Linn and Doran 1983.

bulk density and gravimetric water content, but its application describes microbial activity for many soils. In contrast, the effects of water content or soil water tension on microbial activity are quite soil specific and as such may be more difficult to incorporate into a model (Stanford and Epstein 1974, Van Veen and Paul 1981). Significant temperature-moisture interaction affecting the rate of microbial activity has been observed (Cameron and Kowalenko 1976, Cassman and Munns 1980), so the relationship of %WFP and microbial activity may vary with temperature. Also, because of differences in pore size and distribution among soils, soil type may affect the relationship.

EXAMPLE FOR MODELING MICROBIALLY INDUCED N CHANGE

We have described the dominant physical and chemical factors which influence the rate of microbial activity in soil. Using denitrification as an example, the equation below is presented to illustrate how these relationships may be converted into mathematical expressions useful for constructing models.

$$\frac{dN}{dt} = k \left(\frac{[NO_3]}{K_N + [NO_3]}\right) (T_f)(WFP_f)(pH_f)$$

Selection of a maximum base rate for a microbial process and modification of that rate by terms decribing the effect of an environmental regulator results in a biologically more accurate model and would be appropriate for process level models. In this equation, the base rate is selected from the relationsip of denitrification potential and water-soluble carbon concentration (fig. 2) and modified by terms describing the effects of nitrate concentration, temperature, aeration, and pH.

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ESTIMATING AMMONIUM ADSORPTION ISOTHERMS FOR MIXED SUSPENSIONS AND THE ORGANIC-N/ORGANIC-C RELATIONSHIP USED IN THE SWAM CHANNEL SEGMENT MODEL

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INTRODUCTION

When streams converge or surface runoff enters a reach of a stream, the sediments in each flow component exchange chemicals with the mixed solution and indirectly with each other. Estimates of the postmixing solution concentration and mass of chemical retained by the suspended solids must be obtained to predict the mass of a chemical transported downstream from a confluence, as sediment settles and transformations occur in solution.

The purpose of this paper is to demonstrate a tool to predict the partitioning of ammonium between soluble and adsorbed phases of mixed suspensions and to present a method for determining isotherm parameters from common soil properties.

PROGRAM DEVELOPMENT

The total mass of a chemical at a confluence is the sum of that in the solution and solid phases. If no transformations occur and adsorbed chemical is the only solid phase, the change of mass in solution is equal and opposite to the change in the mass of chemical adsorbed. This materials balance expression is given in equation 1 for a two-component confluence with zero-intercept linear adsorption isotherms,

$$-TV\cdot(X_{eq}-X_m) = S_a\cdot M_a\cdot(X_{eq}-X_{oa}) + S_b\cdot M_b\cdot(X_{eq}-X_{ob}). \qquad (1)$$

TV = total water volume (V_a+V_b) ; L^3
V = volume

X_{eq} = equilibrium solution concentration ; M/L^3

X_m = weighted average solution concentration ; M/L^3
$= (V_a\cdot X_{oa}+V_b\cdot X_{ob})/(V_a+V_b)$

X_o = solution concentration prior to mixing ; M/L^3

S = isotherm slope ; L^3/M

M = mass of suspended solids ; M

a and b refer to components at the confluence

The equilibrium solution concentration of the combined flows, from equation 1, is

$$X_{eq} = (X_m+(S_a\cdot M_a\cdot X_{oa}+S_b\cdot M_b\cdot X_{ob})/TV) / (1+(S_a\cdot M_a+S_b\cdot M_b)/TV). \qquad (2)$$

When mixing the suspensions causes no change in the adsorption characteristics of the components, the total mass of chemical adsorbed at equilibrium is

$$\text{Adsorbed chemical} = S_a\cdot M_a\cdot X_{eq} + S_b\cdot M_b\cdot X_{eq} \qquad (3)$$

and the slope of the isotherm for the mixed suspension reduces to

$$S = (S_a\cdot M_a+S_b\cdot M_b)/(M_a+M_b) \qquad (4)$$

If the exchange process is better described by Langmuir adsorption isotherms, the linear adsorption terms in equation 1 are replaced with Langmuir terms yielding equation 5. The equilibrium concentration is then determined using the bisection method (Hornbeck 1975) to find the root of equation 5.

$$-TV\cdot(X_{eq}-X_m) = X_{eq}\cdot Q_{ma}/(X_{eq}+K_a) - X_{oa}\cdot Q_{ma}/(X_{oa}+K_a) + X_{eq}\cdot Q_{mb}/(X_{eq}+K_b) - X_{ob}\cdot Q_{mb}/(X_{ob}+K_b) \qquad (5)$$

Q_m = adsorption maximum ; M/M

K = the half-saturation concentration; M/L^3

The adsorption maximum of the mixed suspensions is taken to be a weighted average of the components, and the half-saturation constant is calculated by rearranging the Langmuir equation:

$$Q_m = \Sigma Q_{mi}\cdot M_i/\Sigma M_i$$

$$K = X_{eq}\cdot(Q_m/Q - 1) \qquad (6)$$

Q = mass chemical adsorbed at equilibrium/mass sediment ; M/M

CALCULATION OF ISOTHERM PARAMETERS

When assigning values to the isotherm parameters, the best possible situation is for the user to have measured values for the soil of interest.

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However, when measured values are not available, an alternate means of determining values for the adsorption isotherm parameters is required which uses more readily available data. A method of calculating the slope of the linear adsorption isotherm is presented, based on the Gapon cation exchange equation.

The Gapon cation exchange equation for the exchange of ammonium and calcium may be written as equation 7:

$$\frac{[NH_4X]}{[Ca_{1/2}X]} = \frac{K_g(NH_4)}{(Ca)^{1/2}} \tag{7}$$

where

$[NH_4X]$ = ammonium associated with the exchanger (meq/g)

$[Ca_{1/2}X]$ = calcium associated with the exchanger (meq/g)

(NH_4) = soluble ammonium (mmole/L)

(Ca) = soluble calcium (mmole/L)

K_g = Gapon exchange constant $(mmole/L)^{-0.5}$

Rearranging equation 7 gives a linear expression for ammonium exchange similar to one given by Jackson et al. (1980) for the exchange of trace quantities of radionuclides:

$$[NH_4X] = \frac{K_g[Ca_{1/2}X]\ (NH_4)}{(Ca)^{1/2}} \tag{8}$$

Let

$$S = \frac{K_g[Ca_{1/2}X]}{(Ca)^{1/2}} \tag{9}$$

Then

$$[NH_4X] = S \cdot [NH_4] \tag{10}$$

To calculate the slope, equation 9 of the linear exchange equation, equation 10, assume that all counterions behave as calcium, then

$$CEC = [NH_4X] + [Ca_{1/2}X]. \tag{11}$$

If

$$Ca >> NH_4\ ,\ CEC = [Ca_{1/2}X] \tag{12}$$

and

$$(Ca) = \text{solution concentration.} \tag{13}$$

The solution concentration may be estimated from the electrical conductivity (U.S. Salinity Laboratory Staff 1954) as

$$\text{solution concentration} = 10 \cdot EC \tag{14}$$

Units on solution concentration and EC are meq/L and mmhos/cm, respectively. Since the solution is assumed to be predominantly calcium, a divalent cation, the solution concentration is estimated as five times the EC. Convenient units for (NH_4) and $[NH_4X]$ are mg/L and mg/kg, respectively. Substituting equations 12, 13, and 14 into equation 9 and converting units, the final form of the expression for S, the slope of the isotherm is,

$$S = (K_g \cdot CEC \cdot 1000)/(5 \cdot EC)^{1/2}\ ;$$

$$\text{units L/kg.} \tag{15}$$

The slope of the isotherm is now expressed as a function of more common soil chemistry parameters. Possible sources for the values of CEC, EC, and K_g are the National and State soil characterization laboratories and the USDA Salinity Laboratory. A list of suggested default values for CEC, EC, and K_g is given at the end of this section.

When a Langmuir or Freundlich isotherm describes the adsorption process better than a linear equation, it is assumed that the user had the isotherm parameters available in order to make that judgment.

Default values for K_g, CEC, and EC for estimating the slope of a linear adsorption isotherm

---

Gapon exchange constant:

default value = 0.01 assume ammonium : calcium exchange

source: Bohn, H., B. McNeal and G. O'Connor 1979.

Cation exchange capacity:

default value:

$CEC = -0.92 + 2.24 \cdot (\%\ OC) + 0.56 \cdot (\%\ clay)$

CEC - cation exchange capacity ; meq/g
OC - organic carbon ; %

source: Helling, G., G. Chesters and R. Corey 1964.

relationship at pH 6

Electrical conductivity:

default value = 0.1 to 1.0 mmhos/cm - east to west across country.

Ratio - organic nitrogen to organic carbon ratio:

default value = 0.06 to 0.09
west to east
south to north

source: Brady, N. C. 1974.

ESTIMATION OF ORGANIC NITROGEN

Nitrogen transformations enroute from field edge to stream bank are not simulated in the SWAM model, and travel times in these small watershed streams are thought to be sufficiently short to allow nitrate and organic nitrogen to be treated as conservative substances. Therefore, the outflow nitrate nitrogen concentration is simply the volume weighted average of the inflow concentrations. The inflow organic nitrogen concentrations are taken to be a fraction of the organic carbon concentration and are calculated by multiplying organic carbon by the ratio of organic nitrogen to organic carbon in each soil. This approach is taken because organic carbon is a variable common to a number of other submodels, including the pesticide and impoundment models of SWAM, and because a small range of values for the ratio of nitrogen to carbon applies to a great many soils. Much research regarding the carbon to nitrogen ratio has been performed over the years, and the Soil Conservation Service, the soil characterization laboratory, and State soil laboratories should prove valuable as sources of data for many soils. In addition, data sets organized for other national or regional modeling efforts such as the EPIC model (Williams et al. 1982) may provide input information for soils of interest. Suggestions for default values for the ratio of organic nitrogen to organic carbon are presented above.

METHODS AND MATERIALS

Adsorption isotherms of ammonium for a number of soils were determined at 23°C by batch equilibration techniques. Triplicate 1:5 mixtures of 5 grams of soil to 25 mL of solution containing 1,2,5,10,20, or 50 p/m ammonium in 0.001, 0.003, 0.005, or 0.01M $CaCl_2$ were used in the adsorption studies. The soil and solution were placed in 50-mL polyethylene centrifuge tubes sealed with screw caps. Each tube was shaken for 1 hour, and a 10-mL aliquot removed for analysis by steam distillation (Bremner and Keeney 1965). The adsorption data were fitted to equations for linear, Freundlich, and Langmuir isotherms. The Freundlich and Langmuir equations were linearized prior to least squares analysis. The linear form of the Langmuir equation is equation 10 of Veith and Sposito (1977). Adsorption isotherms were also determined for mixtures of the original soils, and these were compared to predicted isotherms for the mixed suspensions.

RESULTS AND DISCUSSION

The soil materials used for this experiment were collected in a small watershed in central Pennsylvania or from a strip mine spoil pile.

A shaking-time study indicated that a 1 hour's shaking was sufficient to bring the samples to "equilibrium."

Goodness of fit as defined by the standard deviation about the nontransformed line (Syx), table 1, shows that over the range of ammonium concentrations used, the adsorption data for the WG and Berks soil materials give best fit to the Langmuir adsorption equation, while a straight line equation gives a somewhat better fit for the mine spoil material. The mixtures with WG also show the best fit to the Langmuir equation, while the Berks:spoil pair, like the spoil alone, is fit somewhat better by a straight line.

Table 1.--Goodness of fit for ammonium exchange data to adsorption isotherms

Isotherm Soil material	Linear	Freundlich	Langmuir
	----------- Syx (p/m) -----------		
WG	1.79	2.22	0.67
Berks	2.20	2.52	1.44
Spoil	1.30	1.61	1.67
Berks:WG	1.70	1.75	0.84
WG:Spoil	1.37	1.24	0.22
Berks:Spoil	1.27	1.65	1.65

All components at a confluence must have isotherms of the same form to use this technique. Based on the standard deviation of the points from the best-fit lines for all the soil materials, the Langmuir isotherm appeared the most appropriate form to use. Therefore, following the procedure described in the development section, Langmuir equations were calculated for each of the mixed soil suspensions.

Root mean square deviations of the measured from predicted lines (table 2) show that over a range of ammonium concentrations up to 40 p/m, the error made using the predicted line to describe ammonium partitioning is similar to that using the measured line. The predicted and measured lines are more similar for mixtures where both members of the pair conformed more closely to the Langmuir isotherm.

Equilibrium concentrations for the mixtures and solutions used during the experimental determination of the adsorption isotherms were calculated with equation 5. Good agreement was obtained between the measured and predicted concentrations, as indicated by the root mean square deviation (table 2) of the data. The good agreement is an indication that the Langmuir equation adequately describes the exchange of ammonium and that the exchange exhibits little hysteresis. Because the isotherms for each component of a mixture, and not the isotherm predicted for the mixture, are used to estimate equilibrium solution concentration, the agreement between measured and predicted concentrations is better than between fit and predicted adsorption isotherms.

Table 2.--Root mean square deviations of measured and predicted Langmuir equations for mixed suspensions

Mixture	RMS deviation		
	Measured line from data	Predicted from measured line	Measured from predicted conc
	---------- p/m ----------		
WG:Berks	0.84	0.20	0.12
WG:Spoil	0.22	2.54	0.36
Berks:Spoil	1.65	0.80	0.63

NOTE: These RMS deviations are for solution concentrations of 1 to 40 p/m.

Isotherms were fit to data measured in solutions with background $CaCl_2$ concentrations of 0.001, 0.003, 0.005, and 0.01M. The slopes of the linear isotherms fit to these data were used to evaluate estimates of isotherm slopes made using equation 15. The fit and estimated slopes for one of the soils are shown in figure 1. When all of the ammonium data for each $CaCl_2$ solution were used to fit the isotherm, the estimated slopes matched the fit slopes well at high $CaCl_2$ concentrations and at EC in the range 0.3 to 1.0 mmhos/cm but matched quite poorly at lower $CaCl_2$ concentrations. When only the data measured in the three lower ammonium concentration solutions (where the data were more nearly linear) were used to fit the isotherms, the agreement between fit and estimated slopes is somewhat better; however, it is still poor at low $CaCl_2$ concentrations. The poor agreement at the lower $CaCl_2$ concentrations likely indicates that the Gapon exchange coefficient is not a constant value over this range of solution concentrations. A value of 0.01 is suggested for the Gapon exchange coefficient in the above list of default values. The data collected indicates that a value of 0.03 is more suitable for these soils.

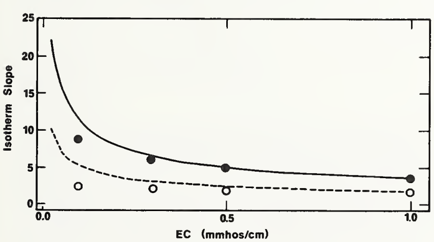

Figure 1.--Best fit and estimated slopes to ammonium adsorption isotherms in solutions of varying $CaCl_2$ concentration. EC equals molarity of $CaCl_2 \div 5$. The upper set of points results when the three most dilute ammonium solutions only are used, while the lower set of points results when all six ammonium solutions are used. The lines are estimates made with equation 15.

A simple procedure is presented which can be used to accurately describe the partitioning of a chemical between solution and adsorbed phases at stream confluences. This procedure is an obligatory step in the estimation of downstream transport. Although ammonium is used in this example, the approach could be applied to any species exhibiting a well defined "adsorption" isotherm.

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GREEN CROPS AND THEIR RESIDUES: A SOURCE OF SOLUBLE PHOSPHORUS IN AGRICULTURAL RUNOFF

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INTRODUCTION

The Water Quality and Management Program under Section 208 of P. L. 92-500 requires that each State plan and implement programs to achieve water quality goals by decreasing both point and nonpoint pollution. As the leaching of green crops and residues contribute significant and variable quantities of soluble plant nutrients, these processes are essential components of a small watershed chemical transport model.

For the United States, crop residues result in the incorporation of approximately 8 to 10 t of dry matter/ha•yr. Residue from dryland wheat totals 2 to 8 t/ha•yr as compared with 2 to 16 t/ha•yr for corn stalks. On an annual basis, crop residues release significant quantities of phosphorus (P) to soil systems. For example, residues of corn, soybean, small grain, and cotton in the United States account for 225,700, 81,200, 107,700, and 14,300 t of P per year, respectively.

Objectives of this manuscript are to discuss through a review of the current literature the factors most important in residue decomposition and the leaching of green crops and their residues as a source of nutrients in agricultural runoff.

LEACHING OF CROP RESIDUES

Moisture

In general, adequate soil moisture and high relative humidity increased the degradation rate of surface applied straw residues (Sain and Broadbent 1975). Soil respiration rates usually achieve a maximum between 0.05 and 0.33 bar soil moisture tension with decreasing rates of residue decomposition at either high or low soil moisture tension values (Reddy et al. 1980). Compared to continuously moist conditions, alternate periods of residue drying and wetting may also increase the release of inorganic P leached from plant tissue (Cowen and Lee 1973).

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Temperature

The optimum temperatures for the biological decomposition of plant residues range from 30 to 40°C. If temperatures are below this optimum range, a temperature increase will usually increase the rate of decomposition. At low temperatures reaction rates may increase 2 to 4 times for each 10°C rise in temperature, as compared to 1.5 times for increases at higher temperatures (Reddy et al. 1980). Other temperature effects, such as freezing and thawing cycles, may also increase the release of P from plant residues.

Biological Factors

The presence of growing plants may affect the release of P from residue added to soil systems. The presence of growing oat plants led to a significant increase in the net release of P^{32} added as labeled plant material to a high and low P soil (Blair and Boland 1978). Similarly, the presence of growing plants was thought to act as a driving force to shift less labile P forms to solution P forms which were more readily available for plant uptake (Dalal 1979).

Soil Fertility

Soil fertility can directly and indirectly affect the release of plant nutrients. Optimum soil fertility will increase not only crop yield and, hence, residue amounts, but also the nutrient content of the plant tissue. In addition, optimum soil fertility and soil reaction assure an adequate microbial population, essential to residue decomposition. Under cropping conditions of low P fertility (no P applications for 24 years) corn residues contained 0.28 percent P compared with 0.43 percent P when corn was fertilized with 49 kg/ha P (Nielsen and Barber 1978).

Residue Management

Residues incorporated into the soil are placed in intimate contact with microorganisms and, hence, undergo faster rates of decomposition. For example, k values for wheat straw decomposition increased in the order buried > on surface > above surface (Douglas et al. 1980).

In addition to the direct release and leaching of P from residues undergoing decomposition, residues would also be expected to increase the equilibrium phosphorus concentration (EPC) of surface soils. For example, in laboratory studies, several PO_4-P sources, including chemical, chemical plus straw, straw, manure, and other organic residues markedly increased the EPC values of several soils (Dalal 1979, Singh and Jones 1976).

Nutrient Ratios

As with nitrogen (N), there is a critical level of P in carbonaceous material which serves as a balance point between immobilization and mineralization. For natural carbonaceous products, this balance point is about 0.2 percent P (Black and Reitz 1972). Thus, P mineralization should follow C mineralization, provided the C/P ratio of the carbonaceous material is below a critical level, about 200:1 or less (Blair and Boland 1978).

Ratios of C/N are also important in the decomposition of plant residues. Critical N contents are 1.5 to 2 percent, and C/N ratios of 20 to 25 are needed for decomposition to proceed (Smith and Douglas 1968). Recent crop-residue-decomposition investigations indicate that the difference between actual and potential rates of residue decomposition reflects a reduction in the rate of decomposition when not enough N is availabe, that is, (dc/dt) actual = μN (dc/dt) potential. The term μN is a reduction factor which is a function of the ratio of the potential rate of C residue decomposition to the total amount of N available (Molina et al. 1983).

While C:N:P ratios are important in determining the amount of net P mineralized, knowledge is also required of the total amount and forms of P present in residue tissue when estimating the quantities of P released during decomposition. In general, agricultural crops contain 0.05 to 0.5 percent P in their tissues.

Crop Residue Decomposition Models

Experimental evidence indicates that decomposition of crop residues best follows the rate equation for a first-order reaction, thus:

$$-\frac{d(A)}{dt} = k(A).$$

Decomposition of C^{14} labeled wheat straw followed the expression $C_t = C_o e^{-rt}$ where C_o = percent residue at t = 0; t = time in years; C_t = percent residue remaining at time t, and r = $\ln 2/t_{1/2}$ (Douglas et al. 1980, Sauerbeck and Gonzales 1977). After an initial rapid loss of C, the mineralization of P from C^{14} and P^{32}-labeled white clover buried in soil closely followed C mineralization according to first-order kinetics (Dalal 1979). Simple power functions also describe cumulative carbon losses as a function of time (Pal and Broadbent 1975; Sain and Broadbent 1975). A recent model designed to describe the degradation of plant residues and other organic wastes takes into account environmental variables such as temperature and soil moisture and is presented as follows (Gilmour et al., 1977):

$$k = 2.303/(t_2-t_1) \log C_1/C_2$$

Plant residue decomposition may involve both slow and fast reactions, reflecting the relative ease of degradation for different organic constituents. Thus, often a double-exponential equation gives the best fit to residue decomposition data, that is, $Y = Ae^{-k_1 t} + (100-A)\, e^{-k_2 t}$ where Y is the percent C remaining in the soil at time t (Cheshire et al. 1979).

For grassland ecosystems, it was recognized that decomposition for a pure substance at a constant temperature and water tension could be represented by simple first-order reaction kinetics, that is, $X_t = x_o e^{-kt}$. However, it was also acknowledged that decomposition of grasses involved two different fractions, each with a different rate constant. One fraction (labile) consisting of sugars, starches, and proteins, underwent decomposition relatively rapidly as compared to a second more resistant fraction consisting of cellulose, lignins, fats, tannins, and waxes. Thus the final form of the equation is similar to that presented earlier (Hunt 1977).

$$At = Se^{-kt} + (1-S)\, e^{ht}$$

where S = the initial portion of labile material, 1-S = the proportion of resistant material, and k and h = reaction rate constants for labile and resistant components, respectively.

A model, very similar to that presented above, has been developed to describe the decomposition of crop residues and other wastes. As before, decomposition is assumed to follow first order kinetics for different phases of decomposition:

$$-\frac{dC_i}{dt} = k_i C_i; \text{ and } C_{t_i} = C_i\, e^{-k_i t}$$

where i = decomposition phase 1, 2, or 3
C_i = organic C at beginning of phase 1
C_t = organic C remaining
k_i i= first order rate constant
t = time in days

The residue amount available for decomposition in phase 1 is represented as D_1 (labile fraction, easily decomposable) and phase 3 as D_3 (residual fraction). No phase 2 decomposition was observed for plant residues. The quantity D_1 was related to, and could be estimated from, the C/N ratio where:

$$D_1 = 86.64 - 13.95 \ln (C/N)$$

This model also provides a means to correct for temperature, soil moisture, and type of residue application, as given below:

Temperature

$k_{i2} = k_{i1}\theta^{(T_2-T_1)}$, where θ ranges from 1.04 to 1.12 with an average of 1.07 ± 0.03

Soil Moisture

$Fm = 1.223 + 0.201 \ln \psi$ for $(0.02 \leqslant \psi \leqslant 0.33)$

$Fm = 0.874 - 0.115 \ln \psi$ for $(0.33 \leqslant \psi \leqslant 10.0)$, where ψ is soil moisture in bars

Type of Residue Application (F_{ma})

Residue	Incorporated	Surface Applied
Corn stalks	1.0	0.51
Wheat straw	1.0	0.37
Rice straw	1.0	0.63

Thus, when all corrections are taken in consideration, the final equation for the reaction rate constant becomes

$$\overline{k}_{12} = k_{11}\theta^{(T_2-T_1)} F_m \cdot F_{ma} \quad \text{(Reddy et al. 1980)}$$

Values of k and h (a second rate constant) can be assumed to be fairly constant for different organic residues, with their values depending more on temperature, soil water, soil aeration, soil fertility, and pH (Hunt 1977). For the decomposition model developed by Reddy, k_1 values were related to D_1, the percent of added C decomposed in phase 1 (Reddy et al. 1980).

LEACHING OF GREEN CROPS

When the physiological aspects of plant growth are considered, a model to describe the leaching of nutrients from growing plants is more complex than that describing the release of nutrients from crop residues. A model describing the leaching of plant nutrients, such as P, from growing plants must include components of (1) plant growth and nutrient uptake; (2) leachability of living tissue by rainfall as a function of plant age (P extraction coefficient); (3) rainfall dynamics, which include rainfall distribution (plant recovery time), intensity, and amount; and (4) dynamics of leaching chemistry as a function of time.

The loss of nutrients from squash and bean leaves was a linear function of time, and indicated a significant replacement of nutrients into the leaf by translocation during leaching. For squash leaves, < 1 percent of the P applied as P^{32} was leached (Tukey et al. 1958). Other studies indicate that nutrients are lost from plant foliage throughout the growing season, with quantities lost increasing just before maturity and death of the foliage (Sharpley 1981). Throughout the active growing season for corn, the total P in separate plant parts was significantly correlated with water soluble P. About 67, 75, and 87 percent of the total P in leaves, leaf sheaths, and stalks, respectively, were water soluble (Hanway 1962). In other plant materials, water soluble P can account for 69 to 78 percent of the total P (Jones and Bromfield 1969).

In a comprehensive study, simulated rainfall was applied at 6 cm/h to growing cotton, sorghum, and soybean plants as a function of soil type and time interval between rainfall events (Sharpley, 1981). The amount of soluble P in the plant leachate was found to increase with plant age and soil - water stress. A period of 24 hours between rainfall events was needed for P to reaccumulate on the leaf surface. With an increase in plant age from 42 to 82 days, the contribution of plant leachate P to soil surface runoff P increased from 20 to 60 percent (Sharpley 1981).

Data in figure 1 are from a preliminary study on the leaching of soluble nutrients from green cotton plants by artificial rainfall. Rain was applied at (a) 2.5 cm/h for 1 h, and (b) on a second new plant, 2.5 cm/h for 3 h. This experiment was conducted late in the growing season; plant senescence and defoliation were rapidly approaching. For the first hour of rainfall, the plant-runoff-weighted PO_4-P concentration was about 0.15 mg/L, a relatively high value, and decreased to 0.05 mg/L during the last 2 hours. At no time was the plant runoff in contact with the soil surface. Concentrations of PO_4-P in the plant runoff showed relatively good agreement well between the two different cotton plants. Concentrations of PO_4-P in plant runoff were related to time and cumulative plant runoff volumes as logarithmic functions. Accumulative quantities of PO_4-P in plant runoff were related to accumulative runoff volumes as linear functions.

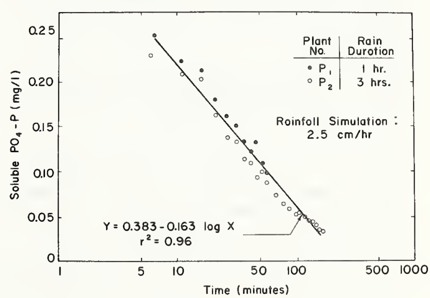

Figure 1.--Soluble PO_4-P concentrations in cotton canopy runoff as a function of time for two different cotton plants.

Many of the minimum and no-till conservation management practices reduce both sediment and sediment associated nutrient yields. However, recent research indicates that some soluble chemical concentrations, including P, N, and C,

are higher in runoff from no-till practices, especially when crop residues are left on the soil surface. While many crop-residue-decomposition models take into account the environmental factors which influence the release and transformation of plant nutrients during decomposition, little is known concerning the kinetics of nutrient leaching from residues by rainfall. In addition, research is needed to further evaluate the leaching of green crops as a source of nutrients as functions of the probability of rainfall and runoff, crop growth stage (leaf area) and plant recovery time. Under natural rainfall, nutrients like PO_4-P leached from the growing plants and their residues become part of the soil-water P matrix and are sorbed by the soil, leached from the runoff extraction zones, and/or transported in runoff.

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TESTING THE NUTRIENT COMPONENTS OF THE EROSION-PRODUCTIVITY IMPACT CALCULATOR (EPIC)

C. A. Jones, J. R. Williams, A. N. Sharpley, and C. V. Cole[1/]

INTRODUCTION

The Erosion-Productivity Impact Calculator (EPIC) is a generally applicable, computationally efficient mathematical model which simulates soil erosion, crop production, and related processes. EPIC has nine major components: weather, hydrology, erosion, tillage, plant nutrients, soil temperature, plant environment control, plant growth, and economics.

The two plant nutrients considered are nitrogen and phosphorus. Nitrogen processes simulated include NO_3^- loss in runoff, organic N transport by sediment, NO_3^- leaching, NO_3^- movement upward due to evaporation from the soil surface, denitrification, immobilization, mineralization, crop uptake and partitioning into economic yield and residue, rainfall contribution, and fixation. Phosphorus processes simulated include soluble P loss in runoff, sediment mineral and organic P transport, immobilization, mineralization, sorption-desorption, and crop uptake and partitioning into economic yield and residue. The structure and preliminary testing of EPIC's nutrient components have been described (Jones et al. 1983, 1984a, 1984b; Sharpley et al. 1983; Williams 1983; Williams et al. 1982, 1983a, 1983b). The purpose of this paper is to describe testing of the plant nutrient component of EPIC. Parts of these results have been published or submitted for publication elsewhere (Jones et al. 1983, 1984b).

METHODS

Published and unpublished data were used to test long-term (20 to 40 yr) simulations of changes in total N and organic C and P and shorter-term (2 to 20 yr) simulations of total N, soil test P, and crop response to soil test P. Initial soil properties and crop management information were obtained from published data and from personal communication. When soil pedon data were unavailable, surrogate data were obtained from published or unpublished Soil Conservation Service pedon descriptions. Initial soil pools of organic C and P, total N, labile P, and mineral P were either input directly or were estimated using equations in Sharpley et al. (1983). Weather sequences at the sites of published experiments were simulated (Richardson 1981, 1982).

RESULTS AND DISCUSSION

Topsoil Organic C, Total N, and Organic P

EPIC simulates the long-term effects of erosion on crop productivity. Erosion may be a slow process, and one of its effects is to reduce soil nutrient pools by removal of those nutrients. Since nutrient cycling through these pools affects nutrient availability to crops, it is important that EPIC produce reasonable long-term predictions of total N and organic P pool sizes. Haas et al. (1957 and 1961) reported on long-term changes in organic C, total N, and organic P in the Great Plains. Topsoil concentrations of total N and organic C and P were reported for virgin soils and for soils cultivated for up to 41 years. EPIC was used to simulate selected treatments from this study. Measurements came from carefully managed experimental plots, and soil erosion from wind was assumed to be negligible. Measured and simulated changes in topsoil total N and in organic P are given in table 1. Means of measured and simulated values of total N and organic P were not significantly different ($P = 0.1$), though mean simulated values were slightly higher than mean measured values. These results suggest that EPIC produces reasonable estimates of decreases in total N and organic P due to cultivation in the Great Plains. The slight overestimation of mean topsoil total N and organic P may be due to constraining soil erosion from wind to negligible values over the duration of the study.

Soil Test P

EPIC can be used to simulate long-term changes in soil test P levels caused by fertilization, rapid P sorption, slow P sorption, crop removal, mineralization, and immobilization (Jones et al. 1984a). Sharpley et al. (1984) provide equations to estimate labile (anion exchange resin extractable) P from commonly used soil tests. Labile P is used for internal calculations of P flows. Soil test P can then be recalculated using the same relationships between soil test P and labile P. Measured and simulated estimates of soil test P are shown in figures 1 and 2. These and other test results (Jones et al. 1984b) suggest that EPIC produces reasonable estimates of changes in soil test P over periods of 10 to 20 years. It is important to note, however, that lime application, leaching of bases, and changes in soil pH due to fertilizer application may change the P sorption characteristics of the soil during the course of the simulation. Factors such as these probably accounted for the abrupt changes in the rate of increase in soil test P reported by Cope (1981) and Hooker et al. (1983), and model estimates of the soil P sorption characteristics should be updated annually to reflect major changes in soil properties.

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Table 1.--Measured and simulated changes in topsoil total N and organic P in the Great Plains[1/]

Location	Duration	Rotation	Total N			Organic P		
			Virgin	Cultivated		Virgin	Cultivated	
				Measured	Simulated		Measured	Simulated
	yr		--------%--------			--------μg P g^{-1}--------		
Havre, MT	31	Sp. wheat-fallow	0.151	0.091	0.106	157	102	116
Moccasin, MT	39	Sp. wheat-fallow	0.300	0.196	0.196	308	183	216
Dickinsin, ND	41	Sp. wheat-fallow	0.293	0.147	0.206	292	148	212
Mandan, ND	31	Sp. wheat-fallow	0.190	0.140	0.145	139	135	108
Sheridan, WY	30	Sp. wheat-fallow	0.152	0.102	0.102	120	113	89
Laramie, WY	34	Sp. wheat-fallow	0.122	0.081	0.083	142	91	103
Akron, CO	39	Sp. wheat-fallow	0.134	0.080	0.082	115	82	77
Colby, KS	31	W. wheat-fallow	0.147	0.110	0.113	174	97	118
Hayes, KS	30	W. wheat	0.162	0.140	0.096	174	97	110
Comanche, OK	28	W. wheat-fallow	0.154	0.078	0.089	128	71	79
Dalhart, TX	39	Maize	0.067	0.043	0.043	84	39	54
Big Spring, TX	41	W. wheat	0.060	0.051	0.035	55	30	23
Mean	--	---	0.161	0.105	0.108	157	99	109

[1/]Measured data from Haas et al. (1957 and 1961).

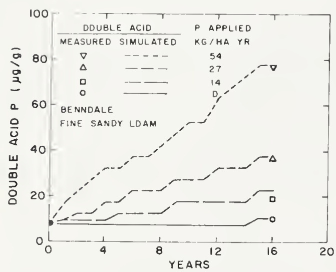

Figure 1.--Measured (Cope 1981) and simulated changes in double acid P.

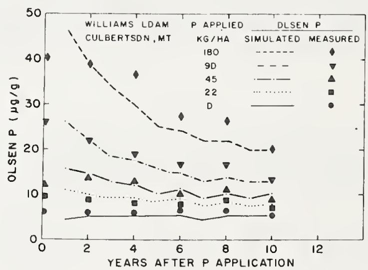

Figure 2.--Measured (Black 1982) and simulated changes in Olsen P.

Crop Response to Soil Test P

It is important that simulated crop responses to soil test P are similar to measured responses. These responses vary among crops, soils, and soil tests. For this reason EPIC allows the user to specify the soil test used to calculate labile P and the critical concentration of soil test P below which response to P is expected for the soil and crop of interest.

Measured and simulated crop responses to soil test P are given in figures 3 and 4 for maize and wheat (Black 1982, Hooker et al. 1983). Measured and simulated responses are similar, both in terms of sensitivity to the soil test P level and the year-to-year variation in crop response to similar soil test P levels.

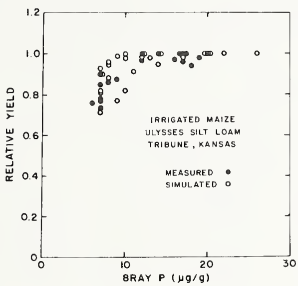

Figure 3.--Effect of Bray 1 P on measured (Hooker et al. 1983) and simulated yields.

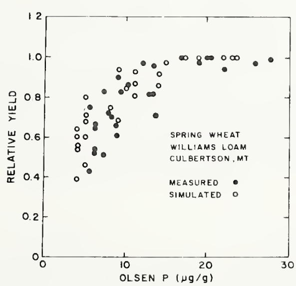

Figure 4. Effect of Olsen P on measured (Black 1982) and simulated wheat yields.

SUMMARY

The plant nutrient components of the EPIC model are designed to use soil chemical, physical, and taxonomic data from the Soil Conservation Service/State Agricultural Experiment Station Soil Survey Investigative Reports. The model simulates many of the major processes affecting N and P availability to crops. The results presented here suggest that the model produces reasonable estimates of (1) the long-term effects of cultivation on total N and organic P contents of the topsoil; (2) the shorter term changes in soil test P contents of the topsoil; and (3) the effect of soil test P contents on crop yields.

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C R E A M S 2--THE NUTRIENT AND PESTICIDE MODELS

R. A. Leonard and V. A. Ferreira[1/]

INTRODUCTION

Planning for control of non-point-source pollution, as legislated in the early 1970's, required methods to assess various management practices as potential best management practices (BMPs) for pollution control. CREAMS, a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (USDA 1980) was developed as a tool to help meet these needs. The CREAMS model has been successfully applied to a wide range of problems (DelVecchio et al. 1983, Knisel et al. 1983). The CREAMS model was developed to provide an operational tool in a short time frame using information and technology that could be readily assembled. The hydrology, erosion, and chemistry submodels were developed and tested at different locations by different teams of scientists. Because of this, the erosion component uses a pass file generated from the hydrology model, and the chemistry model uses a pass file from both the hydrology and erosion models. This procedure facilitated early development of an operational model for user application but limited interaction between components. In contrast, CREAMS2 is programmed as a single model with interaction among components. As an example, algorithms that describe daily plant canopy development provide inputs to ET computations in the hydrology components, cover factors used in the erosion component, and pesticide interception factors in the chemistry components.

In addition to the overall programming strategy above, several significant changes or additions have been made in the chemistry components to extend model applicability. The most significant changes are (1) use of comprehensive nutrient cycling concepts, including nitrogen fixation by legumes, (2) description of plant canopy and crop residue leaching of soluble nutrients, (3) addition of vertical pesticide transport components, and (4) addition of an animal waste component. Differences between CREAMS and CREAMS2 are numerous, some of which will be discussed in the report. This report is intended to provide information on basic chemistry concepts in CREAMS2. Comprehensive documentation will be published at a later date.

THE CREAMS2 MODEL

The CREAMS2 model components and operation logic are described by Smith (1984). General simulation logic is shown in figure 1. The user provides information to describe the field and the initial conditions. All management operations to be performed must also be described.

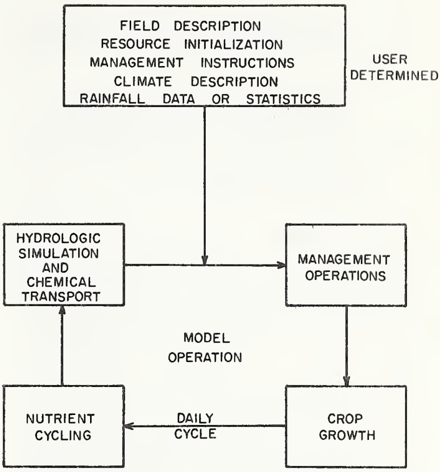

Figure 1.--CREAMS2 general simulation logic

The user also must supply climate statistics and either storm rainfall data or weather-generator statistics.

Simulation proceeds on a daily time step, with shorter times for some processes that occur within the day. Management operations are performed if scheduled and if field conditions permit. Crop growth is then estimated, and nutrient cycle processes are calculated for the day. Finally, hydrologic processes are simulated and all hydrology-dependent functions are performed (for example, erosion and sediment and chemical transport).

The CREAMS2 chemistry model has components for both pesticides and nutrients. Some chemical and physical processes are assumed identical in the two components; other processes are very different or occur only in one component. Four general functions are performed with respect to chemicals, two user-determined and two model-determined. The user provides information to determine

1. Initialization of chemical status of the field, explicitly (initial amounts of chemicals on foliage and in the soil) and implicitly (soil and crop parameters from which chemical pools and properties can be calculated).

2. Management instructions, including definition, description and scheduling of field operations.

The model applies the user-determined information and simulates complex processes such as

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1. Transformations, including chemical decay, mineralization, immobilization, and mineral pool cycling.

2. Transport by rainfall, surface water, sediment, and infiltrated water. The transport process in some cases includes equilibration of solution with soil- and sediment-adsorbed chemicals.

THE NUTRIENT MODEL

In CREAMS2, the soil profile can be described by specifying data for a maximum of 10 horizons with total depth equal to or greater than maximum rooting depth. The soil profile is then subdivided in up to 20 layers for hydrologic and chemical transport computations. Layers are recombined to a maximum of eight for daily nutrient cycling computations. Layers near the soil surface, where tillage and crop residue are more important, are generally kept small. The smallest is at the surface, where a 10-mm depth is assumed. In addition to the surface soil layer, a surface crop residue layer is considered.

Carbon and nitrogen flows through organic pools are described after the work of Parton et al. (1982). Decaying plant material is divided between structural and metabolic components based on N contents of the material and assumed C:N ratios of each component. As respiration and decay proceeds, C and N are distributed between three soil organic matter pools: active, with C/N = 8; slow, with C/N = 10; and passive, with C/N = 11. Plant P:N ratios and assumed P:N ratios of each component are also used to track organic P. Mineralization and immobilization occurs, depending on ratios of available C/N/P and assumed C/N or C/P ratio of organic metabolites produced. All transformation rates are dependent on soil water content and temperature.

Since fertilizers and animal wastes are major inputs to cropping systems, mineral-N pools for both NH_4-N and NO_3-N are included. Crop uptake and denitrification from the mineral pools and N-fixation by legumes are simulated by functions similar to those used in EPIC (Williams et al. 1982). Also, the mineral P component was adopted from EPIC. Phosphorus flows between pools of labile P, active mineral P, and stable mineral P. Rates of flow between pools are governed by soil properties and a number of other factors.

Applications of fertilizer and animal waste are added to the appropriate nutrient pools based on composition of the material applied. Phosphorus fertilizers are added to labile P. Nitrogen fertilizers may contain either nitrate or ammonium. Nutrients from animal wastes are distributed to both organic and mineral pools using available data on animal waste composition.

Transport of nutrients by water occurs from surface residue and crop canopy to the surface soil layer and runoff water, from the surface soil layer to runoff, and between soil layers. Leaching of residue and canopy is computed using functions and data of Schreiber (1984) and Sharpley (1981). Extraction of all soluble and adsorbed chemicals by surface runoff is accomplished using concepts developed in CREAMS for pesticide extraction. Runoff extraction is a function of available concentrations in the surface soil layer, an active surface depth which represents the amount of soil and soil water which can mix with surface water, and a coefficient (Kd) describing how adsorbed substances partition between soil and water. For solution P in runoff, labile P is considered the reactive or supply pool. A buffer capacity (BC) derived from equilibrium sorption relationships and soil properties is used as an approximation of Kd. A Kd for NH_4-N is estimated from soil clay contents. For constituents where Kd is zero, runoff extraction becomes a simple function of the mixing depth, runoff depth, and the amount available.

Concentrations of adsorbed or organic nutrients in sediment are computed from appropriate data on nutrient concentrations in soil, partition coefficients as required, and enrichment ratio derived in the erosion component to account for preferential erosion and transport of the finer soil fractions. All sources of solution P, including residue and canopy contributions, are equilibrated at the field edge with the predicted sediment using an equilibrium phosphorus concentration (EPC)--buffer curve relationship described by Kunishi and Taylor (1977).

Nutrient transport between soil layers is computed from water flux and applicable value of adsorption coefficient as described by Smith (1984).

THE PESTICIDE MODEL

Initialization at the start of a simulation consists of a description of each pesticide to be considered. As many as 20 pesticides are defined by name, chemical properties, and an estimate of the amount of residual pesticide in each soil horizon. The residual allows the user to account for previous applications of mobile, persistent, or recently applied chemicals.

Pesticide applications are user-defined in terms of amount, date, and method of application. In cases of aerial application, the chemical is distributed proportionately into off-site application losses, soil surface interception, and foliar interception. The user may specify the proportions or may estimate only the loss fraction, and the model will estimate foliar and soil interceptions based on current crop cover. The user-defined proportions allow simulation of foliar- or soil-directed spray. Other application methods include surface application, with or

without soil incorporation, injection, and chemigation (application in irrigation water).

As in CREAMS, CREAMS2 assumes a pseudo-first-order decay of pesticides applied to soil or foliage. Decay constants for each pesticide are user-specified. As in CREAMS, the user also provides estimates of upper limits for percentage of washoff of the pesticide remaining on foliage when rainfall occurs. However, in CREAMS2 foliar washoff is proportioned between that added to the surface soil residue before runoff begins and that added directly to runoff. Percentage of canopy washoff is estimated as a function of rainfall amount using information on washoff pattern for a number of pesticides supplied by Willis et al. (1982).

Extraction into runoff and partitioning between solution and sediment are computed by functions analogous to those for nutrients. However, in CREAMS2, values for Kd for the specific soil are computed in the model from Koc values input for each pesticide and organic carbon content of the soil. The Koc is an adsorption coefficient based on organic carbon present in soil and is assumed constant for each pesticide.

A major addition to the pesticide model in CREAMS2 is vertical transport throughout the entire root zone. This capability is aimed at problems of pesticides emerging below the root zone and posing a potential hazard to groundwater. In model application, interactions between soil properties, pesticide properties (persistence and mobility) and rainfall pattern can be examined. For illustration, consider model outputs in figure 2 for two highly persistent, very soluble pesticides in a hypothetical situation. The soil profile consists of three horizons with different organic carbon (oc) contents: a 15-cm layer with 2 percent oc; a 15-cm layer with 1 percent oc; and a 30-cm layer with 0.01 percent oc. Rainfall of 1.2 cm each day moves significant amounts of the pesticide with a Koc = 1 (figure 2a) through the soil profile in 30 days. In contrast, under identical conditions the pesticide with a Koc = 100 (figure 2b) remains mostly in the surface horizon.

SUMMARY OF CREAMS--CREAMS2 DIFFERENCES

The limited scope of this report prevents complete discussion of all differences between CREAMS and CREAMS2. Most differences are briefly summarized in table 1, where the various processes and options are compared.

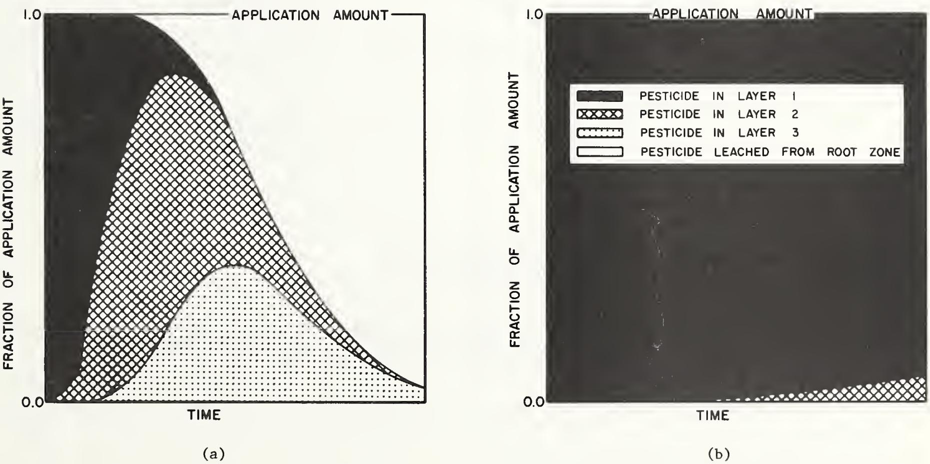

Figure 2.--Results of hypothetical CREAMS2 run. Root zone consists of three horizons: (1) 15 cm with 2 percent organic carbon (oc); (2) 15 cm with 1 percent oc; and (3) 30 cm with 0.01 percent oc. Pesticide in figure (2a) has Koc = 1; pesticide in (2b) has Koc = 100.

Table 1.--CREAMS:CREAMS2 Chemistry component differences

Function/Process	CREAMS	CREAMS2
Chemical application	User-determined fractions of offsite pesticide lost, foliar-intercepted, and soil-intercepted.	New application methods possible, including chemigation and aerial spraying options. Model computes interception fraction based on canopy development.
Chemical transport		
1) Surface	Runoff interacts with top centimeter of soil.	Crop residue layer above soil surface considered in addition to top soil centimeter.
	Foliar washoff added to soil top centimeter.	Washoff partitioned between soil surface and runoff.
2) Subsurface	Root zone single, homogenous layer.	Root zone multilayered for hydrologic and chemical transport calculations.
	Pesticides not tracked below top centimeter.	Pesticides tracked through root zone.
Sorption	Kd partitioning coefficient used for pesticides.	Pesticide Kd calculated from Koc and soil organic carbon content; nutrient sorption function of soil characteristics.
Nutrients		
1) Concepts and pools	Transformations from single soil organic matter pool.	Transformations consider multiple pools for crop residue and soil organic matter.
	NO_3-N and PO_4-P inorganic pools.	NH_4-N pool added for animal waste and ammonium fertilizer applications.
	Single lumped pool for soil P.	Phosphorus model expanded to include labile and mineral P; canopy and residue washoff also considered.
		N-fixation by legumes considered.
2) Environmental variables	Air temperature used to drive nutrient transformations, averaged over periods of time between rain events.	Soil temperature modeled, daily time step used; root zone layered.
	Soil moisture lumped in time and space, averaged between storms for entire root zone.	Daily soil moisture by layer used in nutrient cycle calculations.

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SWAM - THE CHEMICAL MODELS USED IN THE CHANNEL SYSTEM

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INTRODUCTION

The chemical submodel of SWAM includes a routing model and phosphorus, pesticide, and nitrogen algorithms. The submodel is designed to simulate chemical gains, losses, and redistributions from the combining of surface and/or subsurface sources, inflows, sediment deposition, sediment resuspension, and the recharge of channel flow to groundwater.

The assumptions made by use of the model, the input data needs, and output data are presented and described in the Appendix. See SWAM Documentation, Volume 2, Users Manual, for more detailed information. The complete SWAM model is discussed in Alonso and DeCoursey, this volume.

CHEMICAL ROUTING MODEL

The chemical routing model, a mass balance model, assumes that advective transport dominates the effects of longitudinal dispersion. It mathematically describes the change in chemical concentration within the channel as the sediment-laden water moves from channel entry ($t = t_o$) to exit ($t = t_L$), using the Lagrangian scheme

$$C(L,t_L) = C(0,t_o) + \int_{t_o}^{t_L} W_s[x(t),t]dt - \int_{t_o}^{t_L} \alpha[x(t),t]\, C_p[x(t),t]dt \qquad (1)$$

In this equation, $L = x(t_L)$ = the length of the channel; $C(0,t_o)$ = the instantaneous chemical concentration in the upstream inflow to the channel segment; $C(L,t_L)$ = the chemical concentration of the flow exiting the channel segment; $W_s(xt)$ = rate of dissolved chemical addition from (tributaries) or losses (groundwater recharge and water withdrawals) to external sources; $\alpha(x,t)$ = settling rate coefficient for suspended sediment; x = distance in streamwise direction; t = time, $C_p(x,t)$ = concentration of chemical constituent sorbed to suspended sediment.

The changed chemical concentration of the parcel occurring enroute results from the two integrals of the equation. The first integral computes the change in chemical concentration in the parcel due to external chemical sources or sinks such as lateral runoff, groundwater return, and channel transmission losses. The second integral computes chemical losses associated with sediment deposition. In practice, the solution of equation 1 is based on the time averaged rather than instantaneous concentrations.

The individual chemical algorithms, which are part of the first two terms on the right side of equation 1, contain mixing processes and equilibrium isotherms. The equilibrium isotherm -- considered linear, except as one option for NH_4 sorption -- takes the general form

$$C_s = KC_{sol} + A \qquad (2)$$

where A = 0 for NH_4 and pesticides, C_s = concentration on sediment, C_{sol} = concentration in solution, K = equilibrium sorption constant.

Combined with mass inflow information, the equilibrium isotherm takes the form used in equation 1

$$C_s = M/(S + Q/K) \qquad (3)$$

where we assume A = 0 for simplicity of calculation, M = chemical mass, S = sediment mass, Q = water mass, and K = equilibrium sorption constant.

PHOSPHORUS ALGORITHM

The phosphorus algorithm computes three different phosphorus (P) fractions. These are total P, algae-available P and the labile P which includes the rapidly desorbable (sorbed) and soluble P fractions (figure 1).

Total P

Chemically, the total P fraction contains all P species ranging from the very reactive and bioavailable labile P to mineral P forms, the latter not being bioavailable and converting to bioavailable P forms at geologic rates. Total P load through the channel system is computed as the sum of the labile and difficultly desorbable P (DDP) load

$$\text{Total P} = \text{DDP} + \text{labile P} \qquad (4)$$

Chemically, the DDP fraction includes algae-available and unavailable P forms and is associated with the sediment. These P forms are not desorbable or slowly desorable over the long term. Using a

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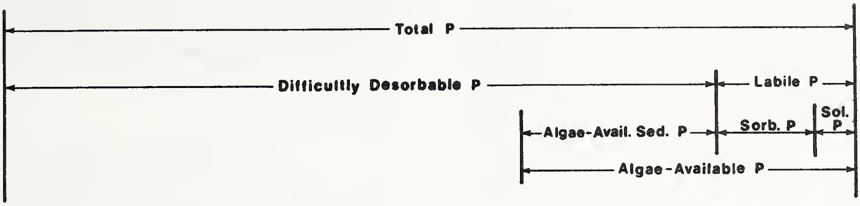

Figure 1. Relationship of different phosphorus fractions.

rearranged equation 4, the algorithm computes the DDP fraction from input total and labile P values supplied by the user. The DDP fraction can increase by P fixation or decrease by P release as described in the labile P section. Loss of the DDP fraction by sediment deposition is defined as

$$DDP_d = DDP_i \times SS_d/SS_i \tag{5}$$

where d = deposited, i = inflow and $\underset{\sim}{SS}$ = sediment mass converted to specific surface, m^2. The conversion is explained in the labile P section.

Algae-Available P

The algae-available P fraction includes the soluble P, sorbed P and the algae-available part of the DDP. The algae-available P in soils, suspended sediments or bottom stream sediments is variable, but generally accounts for 20-40% of the total P fraction (Hegemann et al., 1983; Dorich et al., 1984). It normally excludes the mineralogical and stable organic P fractions which can account for much of the total P in soils. The algae-available P (AAP) load is

$$AAP = AASP + \text{labile } P \tag{6}$$

where AASP = algae-available sediment P load. From a rearranged equation 6, the algorithm computes AASP from input AAP and labile P values supplied by the user. The AASP fraction can increase by P fixation or decrease by P release as described in the labile P section. Computing the loss of the AASP fraction by sediment deposition is analogous to that described in equation 5.

Labile P

The labile P is the sum of the rapidly desorbable P on sediment and the soluble P. At equilibrium, a linear sorption isotherm, analogous to equation 2, is used to relate the labile P (I) sorbed on sediment to the equilibrium phosphorus concentration (EPC) in solution. The method used for computing labile P uses three innovations: the governing equation, a P fixation/release routine, and the concept of specific surface rather than sediment mass. In sequence, the computational method (1) mathematically combines labile P from two tributaries into a combined pool of sorbed labile P to form one equation; (2) mathematically combines the solution P inputs from the same two tributaries into a combined pool to form a second equation; and (3) then solves these two equations simultaneously to obtain a new isotherm, EPC, and I values. The output EPC is the soluble P, and the output labile P (I) is the sorbed P concentration. The governing equation, P fixation and release, and the use of specific surface are discussed further.

The governing equation and sorption isotherm bear great similarities and are closely related. The isotherm for a single soil is

$$I = K(EPC) \tag{7}$$

and the governing equation is

$$I_o = mEPC + b \tag{8}$$

where I_o = intercept I (the I in equation 7 extrapolated linearly to zero EPC), EPC = EPC in equation 7, m and b are either fitted by regression of I_o on EPC obtained for a number of different soils (isotherm) in the watershed or by mixing P-rich and P-poor soils from the watershed at different ratios. For a more detailed explanation see Kunishi and Pionke, this volume.

The use of a governing equation assumes that a single equation, relating EPC and I_o values, basically controls P sorption at the watershed scale. The equation describes a line which represents a family of isotherms, upon which the individual isotherms fall as points. The governing equation is used twice, once to compute an intermediate EPC value from a composited I value, then to compute the final I from the final EPC. These

final values (output) are reinitialized as input to the receiving reach, and the points (EPC, I) always fit the governing equation.

Use of the governing equation presumes that the major differences in the EPC vs I_o relationship at the small watershed scale are primarily due to different soil fertility levels or particle size distributions rather than major differences in soil mineralogy and chemistry. Significant changes in the slope and intercept of the governing equation could result from major differences in the chemical or mineralogical properties of the soil.

P fixation and release is defined as the respective loss or gain of labile P. When sediments of greatly differing sorbed P concentrations, or sediment and solution of greatly differing EPC and soluble P concentration, are mixed, the labile-nonlabile sediment-P equilibrium is shifted, either increasing or decreasing the labile P pool.

The use of a governing equation with a nonzero intercept (b) predicates that fixation and release occur. In nature, P release occurs when either sediment-free rainfall or groundwater containing little soluble P is mixed with P rich sediment-water inflows. In contrast to release, the computed fixation is much greater and more variable, such as when concentrated P solutions from barnyards, feedlots, or industrial or municipal sites are mixed with P starved sediments. If the intercept is set to zero, neither fixation nor release is computed.

The other source of P fixation in the model operates only when sediment is in both inflows. This is basically a mass weighting technique, which includes a fixation factor (0.00 < FF < 1.00) that is multiplied by the difference between the labile P concentration of the two inflow sediments according to

$$I_{ab} = ((A/B)I_a + I_b - (I_b - I_a)FF)/((A/B) + 1) \quad (9)$$

where a and b designate the respective sediment sources, A and B designate the respective sediment masses.

If the intercept for the governing equation and FF = 0, then <u>no</u> P fixation or release occurs anywhere in the program.

Sediment load (m^2), sorbed labile P concentration (mg/m^2), the sorption isotherms, and the governing equation are all expressed in specific surface units. Sediment mass is converted to specific surface [SS] (m^2/kg) by

$$[SS] = 1000(20\ \%clay + 0.4\ \%si + 0.005\ \%s) \quad (10)$$

which assumes P sorption is a surface phenomenon primarily associated with the inorganic soil surfaces. The inorganic specific surface was computed by the method of Young and Onstad (1976).

The primary objective of using specific surface [SS] is to simplify the computational scheme. The one variable, labile P (mg/m^2), replaces two others: particle size distribution parameters and labile P concentration (mg/kg). Unlike the specific-surface-based computation, the mass-based labile-P concentration on sediment can shift because of shifts in particle size distribution. In contrast, the specific surface-based computations change only in respone to the adsorption or desorption of P.

PESTICIDE ALGORITHM

Similar to the phosphorus model, the pesticide algorithm describes sorbed and soluble pesticide interactions in a channel reach under equilibrium conditions using a linear sorption isotherm. The differences are that the pesticide model always has a zero intercept, does not have a pesticide fixation routine, and assumes that the organic carbon rather than mineral surface controls pesticide sorption.

Similar to the phosphorus model, pesticide losses are computed by lost specific surface rather than sediment mass. In contrast, this is an organic- rather than inorganic-weighted specific surface (m^2/kg) and is defined as

$$[SS]_o = 1000(100\ \%OC + 2.0\ \%clay + 0.4\ \%silt + 0.005\ \%sand) \quad (11)$$

which assumes that soil clays in the environment behave substantially as 1:1 rather than 2:1 expanding layer silicates because of surface coatings and blockages. Using kaolinite as the clay model, roughly a 1000:20 ratio in specific surface would exist between equivalent masses of organic carbon and clay.

In concept, the sorption isotherm is more easily obtained and defined than for the phosphorus system. The equilibrium sorption constant, K, which relates solution and sorbed pesticide at equilibrium, is viewed as made up of two component parameters. One describes the soil property controlling sorption, and the other provides a measure of the pesticide's inherent sorptivity. The K value or K_d is defined several alternative ways to make use of available data and to increase the versatility of the model

$$K_d = K_{oc}\ \%OC/100 = m_{oc}\ \%OC = K_{ss}[SS] \quad (12)$$

where $K_d = C_s/C_{sol}$ at equilibrium; $K_{oc} = K_d$ expressed on the organic carbon basis (see Green, this volume); m_{oc} = regression-fitted $K_{oc} \div 100$ (Pionke and DeAngelis 1980); $K_{ss} = K_d$ expressed on the specific surface basis (Pionke and DeAngelis 1980); %OC = percent organic carbon; [SS] = specific surface area as m^2/g instead of m^2/kg.

Recent reports suggest that K_{oc} is the most useful and defensible form of the coefficient.

This pesticide model does not estimate pesticide losses by volatilization, degradation, or immobilization (plant or microbial uptake).

NITROGEN ALGORITHM

The nitrogen algorithm includes NO_3, organic N, and NH_4. The NO_3 and organic N algorithms are simple conservative models; and, in addition, the organic N model presumes a relationship between the organic N and carbon content of sediment. During routing, NH_4 is distributed using an equilibrium sorption isotherm similar to the phosphorus and pesticide models.

The NO_3 concentration of outflow is computed by

$$(NO_3)_n = \Sigma((NO_3)_i \times Q_i)/Q_t \tag{13}$$

where n = outflow, i = inflows, t = total, q = water volume.

The organic N (ON) of outflow is computed as a function of organic carbon (OC) content and of the inflow soil and sediment mass according to

$$ON = K_{ON}OC \tag{14}$$

where usually $K_{ON} = 0.06 - 0.09$, as developed by Schnabel, this volume.

The NH_4 model offers a linear or nonlinear (Langmuir) sorption isotherm for estimating the redistributions of NH_4 between solid and solution phases. Both isotherms have zero intercepts, so neither NH_4 fixation nor release is computed. The inflow sorption isotherms are mass weighted into one for the combined outflow. For two inflows (a,b) and a linear sorption isotherm, $C_s = K\,C_{sol}$, the mass balance equation takes the form

$$- Q_t\,(C_{sol} - C_{ab}) = K_aS_a\,(C_{sol} - C_a) + K_bS_b\,(C_{sol} - C_b) \tag{15}$$

where Q_t = total flow volume, S = sediment mass, C = NH_4 concentration, K = sorption equilibrium constant, a and b = the initial concentrations of component values, C_{sol} = new equilibrium concentration, and C_{ab} = the flow weighted concentration. C_{sol} is computed from the above equation, then used to obtain C_s as follows

$$C_s = C_{sol}K_{ab} = K_aS_a\,C_{sol} + K_bS_b\,C_{sol} \tag{16}$$

where $K_{ab} = [(K_aS_a) + (K_bS_b)]/(S_a + S_b)$.

In order to compute K_a and K_b, assuming a linear sorption isotherm, the following Gapon cation exchange equation is used

$$(NH_4X)/(Ca_{0.5}X) = K_g\,(NH_4)/(Ca)^{0.5} \tag{17}$$

where NH_4 X and $Ca_{0.5}X$ = concentrations on the soil's cation exchange complex (meq/g); NH_4, and Ca = concentrations in solution (mmole/L); K_g = Gapon exchange constant $(mmole/L)^{-0.5}$. The Gapon equation may be rewritten as a linear equation with zero intercept

$$NH_4X = K(NH_4) \tag{18}$$

where $$K = K_g(Ca_{0.5}X)/(Ca)^{0.5} \tag{19}$$

Then, if all counterions act as Ca and (Ca) >> (NH_4)

$$K \cong 1000\;K_g\;CEC/(5EC)^{0.5} \tag{20}$$

where CEC = cation exchange capacity (meq/g), and EC = electrical conductivity (mmhos/cm). Schnabel (this volume) discusses ways to estimate K_g, CEC and EC using data from soil surveys and from State and Federal soil test laboratories.

The Langmuir isotherm is probably less applicable and will not be discussed here because the user must supply the needed parameters.

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APPENDIX

Summary Tables on Assumptions Made, Input Data Needs, and Output Data Obtained by Use of the SWAM Chemical Model.

Table 1. -- General assumptions made by use of the SWAM chemical model

Assumption	Rationale
Processes controlling chemical loss or gain in system are hydrologic or chemical, but not biological. Thus, biologically caused transformations are ignored.	Water and sediment are either transported, gained or lost rapidly because the model is designed for small (<10 km^2) well drained watersheds. Biological transformation rates are much slower than the hydrologic, sediment transport and chemical rates. Groundwater systems are much less biologically active than the surface system.
Processes controlling the chemical transformation between components or chemically different fractions are not included. Except for the fixation and release of labile P, the rate of such transformations is considered negligible.	In the small, well drained watershed, transport through the channel system is considered sufficiently rapid to prevent chemical transformation from becoming important. Example transformations are: mineralogical to labile P, organic N to NH_4, and NH_4 to NO_3.
The sorbed chemical system is treated as a chemical equilibrium system because a) the rate of dominant hydrologic processes are often much slower than that of the dominant sorption processes and b) the dominant sorption reactions are sufficiently fast to be mostly completed within the selected hydrologic modeling unit.	Considerable evidence exists that adsorption is a very rapid process, often mostly complete within minutes for pesticides, NH_4, and phosphorus. Desorption can be slower and has been reported to take hours to be mostly completed. The basic hydrologic-unit size must be such that the time required for the chemical to be mostly adsorbed or desorbed is less than the hydrologic travel time through the unit. This may be the most critical assumption.
Instantaneous uniform mixing of water and suspended sediment within the basic hydrologic unit, for example, channel segment.	During storm events, mixing and turbulence in stream channels are usually major.
No transfer of chemical mass between moving and stationary phase in channel except for either chemical loss by sediment deposition, subsurface recharge of channel flow, or chemical gain from subsurface return flow.	The model does not include chemical transfer, independent of water or sediment transfer, between the moving suspended load and stationary banks and bottom. Such transfers are least likely to be important when: a) the chemistry and mineralogy of exposed stationary channel sediments are not greatly different from those of sediment in the moving phase, and/or b) the soluble P or NH_4 concentration in stream flow is not greatly different from that in equilibrium with the channel side and bottom sediments. The model does not provide a mechanism for storing or dissipating chemicals deposited in the channel during interstorm periods. This can be a reasonable assumption for sorbed chemicals. For example, exposure of recently deposited, chemically-enriched channel sediment to several days of dilute base flow, potentially desorbs and removes much of the sorbed chemical. The channel sediment. resuspended and reintroduced to channel flow system in a later event, would be largely depleted of desorbable chemical.
Sorption isotherm for phosphorus, pesticides and NH_4 are assumed linear, except for one NH_4 option. The assumption simplifies the model, but is not critical, because the model structure can accommodate a curvilinear isotherm.	The isotherm for many pesticides can be approximated as linear without serious error over a wide range of concentrations. The isotherm for most pesticides, phosphorus, and NH_4 can be linearly approximated over low and medium concentrations.

Table 2. -- Major input data needs to operate the phosphorus, pesticide and nitrogen models[1/]

Model	Parameter-Units	Source
All	sediment mass[2/], kg	SWAM Sediment Transport Model.
All	clay, silt, sand, kg	" " " " Soil Survey Information.
All	water mass, kg	SWAM Hydrologic Model.
P	total P, mg/kg	Determined experimentally or estimated.
P	algae-available P, mg/kg	Determined experimentally or estimated.
P	soluble P, mg/kg	Determined experimentally or estimated if not EPC.
P	EPC and I_o, mg/kg	Determined experimentally or estimated (see Wolf et al., this volume).
P	fixed P fraction, unitless	Determine experimentally, estimated or assume zero (no fixation).
Pest.	K_d[3/] K_{oc}[3/] or K_{ss} (kg/m^2)	Determined experimentally or estimated (see Green, this volume; Pionke and DeAngelis 1980).
Pest. N-org.N	soil org. carbon, kg	SWAM Sediment Transport Model, Soil Survey Information.
N-org.N	K_{ON}, unitless	Determined experimentally or estimated from Schnabel, this volume.
$N\text{-}NO_3$	soluble NO_3, mg/kg	Determined experimentally or estimated.
$N\text{-}NH_4$	K, unitless[3/]	Determine experimentally or from a combination of Gapon's K. Cation exchange capacity and electrical conductivity according to Schnabel, this volume.

[1/] SWAM model provides input data from tributaries.

[2/] Converted to specific surface (m^2) in phosphorus and pesticide program.

[3/] Water mass expressed in kg.

Table 3. -- Major output data from the phosphorus, pesticide and nitrogen models[1/]

Model	Parameters or Variables	Units
P, pest., N	Soluble P (EPC), pesticide and NH_4-N concentration and load.	mg/kg, mg
P, pest., N	Sorbed labile P (I), pesticide, and NH_4-N concentration and load.	mg/kg, mg
P, pest., N	New sorption isotherms.	-
P	Fixed or released P.	mg, %
P	Algae-available P load.	mg
P	Total P load.	mg
P	Sediment P concentration and load.	mg/kg, mg
N	Organic N concentration and load - sediment.	mg/kg, mg
N	NO_3-N concentration and load.	mg/kg, mg

[1/] Data is provided to the user on: losses in channel outflow for the listed chemical parameters; losses of sorbed or sediment associated P, pesticides and N upon sediment deposition; losses of soluble P, pesticides and N upon groundwater recharge of channel flow; gains of NO_3 from groundwater discharge to channel flow.

MODELING CHEMICAL AND BIOLOGICAL PROCESSES IN AGRICULTURAL IMPOUNDMENTS

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INTRODUCTION

Impounded water bodies are complex physical, chemical, and biological systems. A large number of models of lake ecosystems have been advanced in recent years. The degree of complexity of such models ranges from statistical regression equations of chlorophyll against total phosphorus (Vollenweider 1968, Dillon and Rigler 1974, Jones and Bachmann 1976) to sophisticated, hydrodynamic-ecologic simulation models based on chemical mass balance. A partial list of mass-balance models, compiled by Harris (1980), includes Bierman (1976), Bierman and Dolan (1976), Canale and Squire (1976), Cloern (1978), Desormeau (1978), Groden (1977), Ikeda and Adachi (1978), Imboden and Gachter (1978) and Park et al. (1974, 1979). The state of the art of impoundment modeling has recently been reviewed by Krenkel and French (1982).

The complexity of lake models is determined by the degree of physical and biological realism incorporated into the model structure, which in turn limits the range of applicability of the model. For example, the phosphorus-chlorophyll regression models correctly identify phosphorus as a major determinant of accelerated eutrophication on a continental scale, but the regression models give no information about the timing or species composition of an algal bloom (Harris 1980). Thus model complexity is ultimately determined by the modeling objectives.

The principle objectives in modeling chemical and biological processes in agricultural impoundments are related to the prediction and control of nonpoint source pollution. Some specific objectives are

To determine the fate of nutrients and pesticides applied to soils in a watershed,

To investigate long term effects of alternative land management practices and the management of impounded water on the quality of runoff water, and

To predict levels of constituents in impounded water that affect its suitability for agricultural uses.

This paper identifies the chemical and biological processes that could be incorporated into an impoundment model which is to be a component of the Small Watershed Model (SWAM). Mathematical relationships which have been used successfully in previous lake models will be discussed. Features that distinguish farm ponds from natural lakes will be identified, and some potential modeling approaches proposed. Discussion of chemical cycles will be restricted to the major nutrients, nitrogen and phosphorus. Dissipation of pesticides from farm ponds has been discussed elsewhere (see Nash and Isensee, this volume).

CONCEPTUALIZATION OF POND PROCESSES

Figure 1 is a detailed conceptual diagram of chemical and biological compartments in a farm pond. The biological compartments are redrawn from the lake model MS.CLEANER by Park et al. (1979). Chemical sources, sinks, and transformations consist of inflow from the watershed via surface and groundwater flows, adsorption/desorption equilibration with suspended sediment surfaces, chemical and biological transformations (for example, nitrification, plankton uptake,) sedimentation/resuspension, and outflow to downstream segments. Biological compartments consist of phytoplankton, macrophytes, herbivorous and carnivorous zooplankton, fish, and decomposers, with the possibility of several species being important for each category. The amount of biological detail that can be included to model any particular biological compartment varies widely. For example, phytoplankton growth can be considered to be determined exclusively by the rate of uptake of a limiting nutrient; or growth can be determined as the resultant of concurrent processes such as photosynthesis, excretion, respiration, sinking, and grazing, the nutrient uptake and assimilation processes being considered separately (Park et al. 1979). Additional biological detail requires additional parameter values, many of which will be poorly known; but the inclusion of greater detail can be expected to produce more accurate predictions, or at least more realistic variability over the short term (that is, several days to weeks) that the specific parameter values apply.

Most of the models cited above have been written for natural lakes. Thornton et al. (1982) have pointed out differences between reservoirs and natural lakes, several of which may apply to agricultural impoundments and may be important for modeling. Of particular importance to agricultural impoundments is the fact that reservoirs tend to have greater drainage/surface area ratios, areal water loads, and shoreline development ratios, and shorter hydraulic residence times than natural lakes. Consequently runoff events have a much larger potential for dominating the chemical and biological character of farm ponds than in most natural lakes. Since runoff from agricultural lands is often heavily laden with suspended sediment, chemical and biological processes that occur at the solid/solution interface require greater attention than has been given in most lake ecosystem models.

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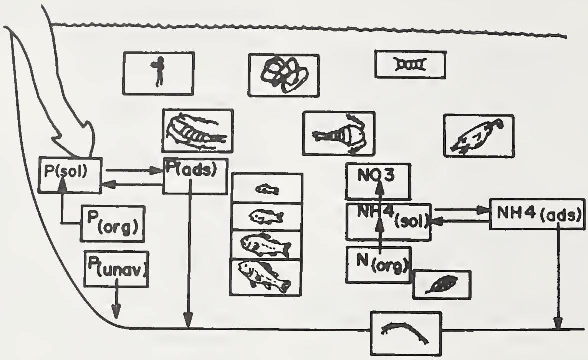

Figure 1.--Conceptual diagram of biological and chemical compartments in a farm pond. Biological compartments consist of phytoplankton and aquatic plants (first level), zooplankton (second level), and fish. Chemical compartments are defined in the text.

ELEMENTAL CYCLES

Phosphorus

Phosphorus in aquatic systems exists in many different chemical forms (Stumm and Morgan 1970). For modeling, the total phosphorus pool must be divided into a number of functional compartments which, with the possible exception of soluble inorganic orthophosphate, cannot be clearly defined chemically. In the model under development, the forms of phosphorus that enter the impoundment are determined by those transported in the stream and groundwater segments of the watershed model. These forms are

Available P, also called soluble P, which is principally soluble inorganic orthophosphate;

Labile adsorbed P, which is phosphorus associated with suspended and bottom sediment that is in equilibrium with soluble P;

Organic P, which is phosphorus entering with the inflow that is associated with sediment organic matter, or autocthonous algal decomposition products that can be transformed to soluble P by microbial remineralization; and

Unavailable P, which is phosphorus associated with sediment that is transformed to labile adsorbed P at rates that are slow compared to sediment deposition.

The partitioning of phosphorus between adsorbed and soluble phases is frequently modeled using a partitioning coefficient, or linear adsorption isotherm,

$$K_D = P_{ad}/P_{sol} \qquad (1)$$

where K_D = slope of the adsorption isotherm (L/g), P_{ad} = labile adsorbed P (microgram P/g adsorbant), and P_{sol} = soluble P(microgram/L). Over a wide range of $[P_{sol}]$, the adsorption isotherm is usually nonlinear, and a higher order isotherm (for example Langmuir, Freundlich) must be used; but at the relatively low concentrations usually encountered in surface impoundments, a linear isotherm may be assummed (Kunishi and Pionke, this volume; Wendt, this volume; White and Taylor 1977). Phosphorus desorption from bottom sediments is usually minimal under oxygenated conditions but may be appreciable under anoxic conditions (Kramer et al. 1972). Models of chemical exchange at the sediment-water interface have been reviewed by Kamp-Nielsen (1983). Another important process in the mass balance of adsorbed phosphorus is resuspension of bottom sediments, and a computational procedure has been given by Sheng (1980).

Nitrogen

As with phosphorus, the functional compartments

of nitrogen that enter the farm pond are determined by the stream and groundwater components of SWAM. Unlike phosphorus, the nitrogen compartments may be more easily identified with chemical compounds. The compartments are

Ammonium, NH_4, which includes dissolved and adsorbed forms;

Nitrate, NO_3, which is in solution only; and

Organic N, consisting of nitrogen in the inflow that is associated with sediment organic matter, plus autocthonous algal decomposition products.

The adsorption of NH_4 to suspended sediments is treated as a linear isotherm, similar to equation 1. The slope of the adsorption isotherm is computed from organic carbon content, percent clay, and cation exchange capacity of the sediment according to the procedure used for streams (see Schnabel and DeAngelis, this volume).

Nitrification, but not denitrification, is included on the assumption that most farm ponds are shallow enough that any hypolimnetic oxygen depletion will usually be brief and intermittent. Nitrification can be modeled as a first order sink and source term in the mass-balance equations for NH_4 and NO_3, respectively:

$$\frac{d[NH4]}{dt} = -KN(T)[NH4] + S1 \qquad (2)$$

$$\frac{d[NO3]}{dt} = KN(T)[NH4] + S2 \qquad (3)$$

where K_N is the temperature (T) dependent nitrification rate constant, and S_1 and S_2 are the sums of all other sources and sinks for NH_4 and NO_3 respectively. The temperature dependence of K_N can be represented (DiToro et al. 1977) as

$$K_N(T) = K_N(20)r^{(T-20)} \qquad (4)$$

where $K_N(20)$ = nitrification rate constant at 20° C (≅ 0.3/day for the San Joaquin-Sacramento River estuaries), and r = a temperature sensitivity coefficient.

Although the concentration of NH_4 may usually be low, it is included because, when available, it is the preferred form for algal uptake; NH_4 is also the form of nitrogen that is remineralized from decomposition of organic matter. Plankton uptake of NH_4 relative to NO_3 can be related to the relative availability of each by a coefficient a (DiToro et al. 1977), given by

$$a = \left(\frac{[NH4]}{Km + [NH4]}\right)\left(\frac{[NO3]}{Km + [NO3]}\right) + \left(\frac{Km}{Km + [NO3]}\right)\left(\frac{[NH4]}{[NH4 + [NO3]}\right)$$

where K_m is the Michaelis-Menton half-saturation coefficient for nitrogen uptake. When $[NH_4]$ is high, a approaches 1 and NH_4 is the form of nitrogen used by algae; when $[NH_4]$ is low and a approaches 0, NO_3 is used.

BIOLOGICAL PROCESSES

The fundamental approach to modeling the biomass of species in aquatic ecosystems has changed little since the pioneering work of Riley (1946). The basic mass-balance equation for a species or trophic level is usually written as

$$\frac{dB}{dt} = (Pg - R - E - M - G)B \qquad (6)$$

where B is the biomass of the species of interest, and P_g, R, E, M, and G are respectively the rates of gross production, respiration, excretion, nonpredatory mortality, and grazing mortality, all per unit biomass. Phytoplankton may have an additional loss term due to sinking, and zooplankton and fish may have additional source terms due to recruitment of younger age classes. In addition, models with one or more spatial dimension may simulate changes in populations due to advection and/or migration. Within this framework, the primary differences among models are in the number of species or trophic levels modeled, the degree of mechanistic or empirical detail in the growth and loss terms on the right hand side of equation 6, and in the treatment of the hydrodynamic transport and environmental forcing functions.

The biological food web illustrated in figure 1, from the model MS.CLEANER by Park et al. (1979), is perhaps the most detailed representation of the biological community in a lake model attempted to date, and is the most complex model that could reasonably be constructed for a farm pond. At the other extreme, the minimum model of the biological community in a farm pond would be a light- and nutrient-limited model of phytoplankton growth. The minimum model may predict the nutrient trapping efficiency of a farm pond at least as well as a complex food web model, but a model including fish would clearly be needed to predict a pond's recreation potential.

SUMMARY AND RECOMMENDATIONS

A great deal of research has been conducted on modeling of lakes and impoundments. The state of the art of modeling mixing and stratification in lakes has advanced so that the vertical temperature distribution can be predicted from routine weather observations with good accuracy, especially in systems that can be considered one-dimensional (Krenkel and French 1982). A great deal of research has also been conducted on relating the terms in equation 6 to environmental conditions (see, for example, Rhee 1982). Some of the resulting relationships have been incorporated into simulation models, which give reasonable predictions of annual variations in populations and major nutrients (DiToro et

al. 1977). Yet some biologists are dissatisfied because the biological relationships derived from steady-state laboratory experiments do not apply to fluctuating conditions in the field (Harris 1980).

Probably the main feature distinguishing farm ponds from natural lakes is the high loading of suspended sediments to the former. It is quite likely that accurate routing of sediments will be more important to the overall prediction of chemical and biological processes in farm impoundments than the detailed, mechanistic formulation of complex biological interactions. In addition, recent studies have indicated that there are interactions (beyond the obvious reduction in light penetration) between suspended sediments and the biological community at all levels--phytoplankton (Avnimelech et al. 1981), zooplankton (Arruda et al. 1983), and fish (McIntyre 1983). Mathematical formulation of these phenomena represents a challenging direction for future modeling of farm impoundments.

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HYDROLOGY AND NONPOINT POLLUTANT CONSIDERATIONS FOR A FRESHWATER WETLANDS MODEL

J. C. Lance[1]

INTRODUCTION

There are many kinds of wetlands at the interface between land and water systems. The principles of water or land systems cannot be easily extrapolated to wetlands. Wetlands are areas where the soil is wet enough to support aquatic or semi-aquatic plants consisting of trees, shrubs, emergents, floating plants and submergents (Weller 1981). The type and amount of vegetative cover varies greatly, depending upon the topography, water depth, climatic zone, and management. Currently wetlands represent about 3 percent of the total land area in the United States and wetlands are being lost at the rate of about 120,000 hectares per year. Although the area occupied by wetlands is relatively small, they are quite important to the overall ecosystem due to their ability to trap sediment, nutrients, and pesticides; attenuate flood peaks; store water; and provide habitat for wildlife. Therefore a wetlands submodel is needed as a part of the Small Watershed Area Model (SWAM) to adequately describe the movement of water and pollutants through watersheds containing wetlands.

On the basis of hydrogeologic factors, freshwater wetlands are divided into riverine, lacustrine, or palustrine systems (Sloey et al. 1978). The principal inflow into riverine systems is surface flow from stream channels. Rivers form marshes directly through their meanders. Extensive riverine marshes are found where major streams form deltas or spread out as braided streams in flood plains. Riparian zones are common in coastal plain regions where channels are shallow and adjacent areas are subject to seepage and flooding.

Lacustrine systems occur where gravel, sand, and soil deposited along the shores of lakes trap water entering from the surrounding watershed. Water levels in these marshes are regulated by the overall water balance of the lake. In many cases, water can exchange freely between open water and the lacustrine wetlands.

Palustrine systems are wetlands which are not confined by channels or marginal to lakes. Such wetlands are isolated from open surface water such that there is not a ready exchange of water, but there may be an interaction with groundwater. In many cases palustine systems were formerly lakes that were changed to marshes by the deposition of material eroded from surrounding areas.

In most of the wetland types water can move through the wetland either as sheet flow or in channels subject to frequent overflow. Wetlands are important to the overall hydrology of watersheds because they hold back flood waters and attenuate flood peaks.

Sedimentation in Wetlands

As water flows through the wetland, the aquatic vegetation and reduced gradients decrease the velocity and cause sediment deposition. Thus, the size and geometry of the wetland determines the length of the flow path and thereby affects sedimentation. Also, the type and density of the vegetation determines the tortuosity of the flow path, flow velocity, and the length of path of flow. Sedimentation in wetlands with well defined channels is quite different from that in wetlands with essentially sheet flow. In wetlands with channels, most of the sedimentation occurs during the periods of channel overflow, and deposition is highest near the channel and decreases with distance away from the channel.

Sedimentation results in trapping of nutrients, pesticides, and heavy metals attached to the sediment. Complex interactions between sediments and plants as well as between sediments and the water column above them determine whether or not pollutants are permanently trapped. Large amounts of sediments and the associated pollutants can be trapped in wetlands. For example, sediment yield estimates for streams in Wisconsin were 90 percent lower in basins containing wetlands than in basins with no wetlands (Novitzki 1979).

NUTRIENT TRANSFORMATIONS

Nitrogen

Nitrogen removal from waters entering wetlands is controlled by a complex array of interacting physical, chemical and biological reactions (fig. 1). Nitrogen enters the wetlands as NH_4-N, NO_3-N, or organic N. NO_3-N is primarily in the dissolved form while NH_4-N and organic N may be associated with either the solution or sediment phase. Most of the microbiological activity in the wetland occurs at the sediment-water interface. Organic material from sedimentation and from plant debris is mineralized there to produce NH_4-N. As oxygen diffuses to the interface from the water column, NH_4-N is oxidized to NO_3-N by the process of nitrification. Then NO_3-N can diffuse into lower anaerobic layers and be reduced to nitrogen gas by the process of denitrification.

Plants may take up either NH_4-N or NO_3-N primarily from the sediment (except floating aquatics which take NO_3-N from the water) and convert it to vegetative material. When the plant dies, the vegetation falls into the water, where some nitrogen is leached from the litter before it eventually settles to the bottom and decomposes. However, some resistant plant material may be buried and eventually converted to peat in continuously flooded wetlands. Also, some nitrogen can accumulate in the wood of

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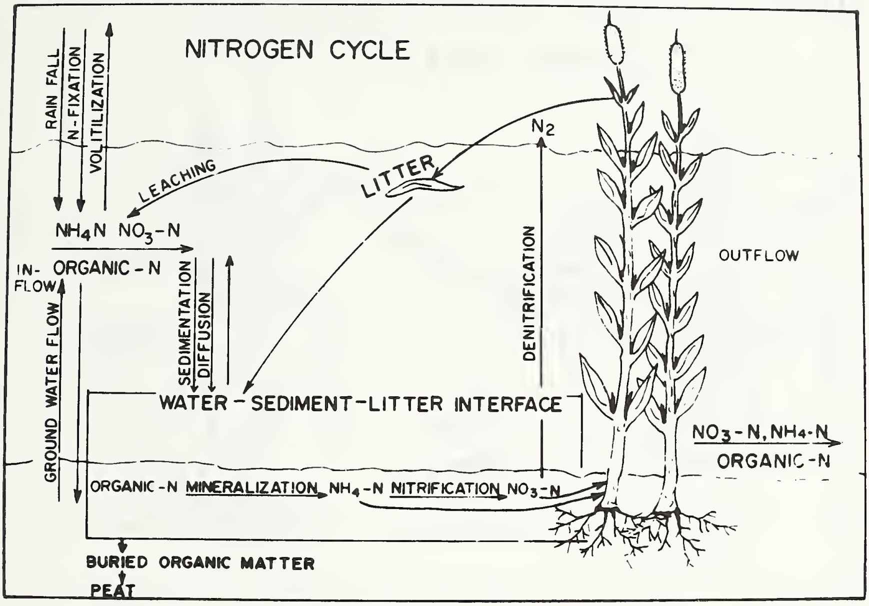

Figure 1.--The nitrogen cycle in a wetland.

forested wetlands.The extent of denitrification is determined by the supply of organic carbon available for dentrifying bacteria and by the detention time of water containing nitrate in anaerobic zones. Since organic material usually is abundant in wetlands, the detention time in reduced zones generally is considered to be the factor limiting denitrification. Denitrification could be quite limited in wetlands where water moves rapidly through the system in well defined channels.

Although denitrification generally is considered to be the pathway with the greatest potential for nitrogen removal in wetlands, N accumulation rates in sediments in a Wisconsin wetland were found to be significant, and N uptake by plants slowed the movement of nitrogen through wetlands (Johnston et al. 1984)

Phosphorus

Organic or inorganic phosphorus entering the wetland may be in solution or adsorbed in sediment (fig. 2). Phosphorus can move back and forth between the adsorbed and soluble phases as the inflow is diluted or enriched with respect to the different phosphorus forms. Generally, most of the phosphorus entering a wetland is removed from the water with the sediment. Phosphorus in the deposited sediment is in equilibrium with dissolved P in the water column. Soluble P can move between the interstitial water in the sediment and the water column via diffusion, with the direction of flow determined by P concentration gradients. Plants take up soluble P, and some of the adsorbed P in the deposited sediment also is available to plants. The P incorporated into vegetation eventually is returned to the water as plants die or leaves are dropped. Much of the P can be leached from the plant material before it settles to the bottom and decomposes. A considerable amount of P can be incorporated into vegetation during the growing season and released in the fall. Some P can be incorporated into peat. Thus the main permanent P sinks in wetlands are both sediment P that is

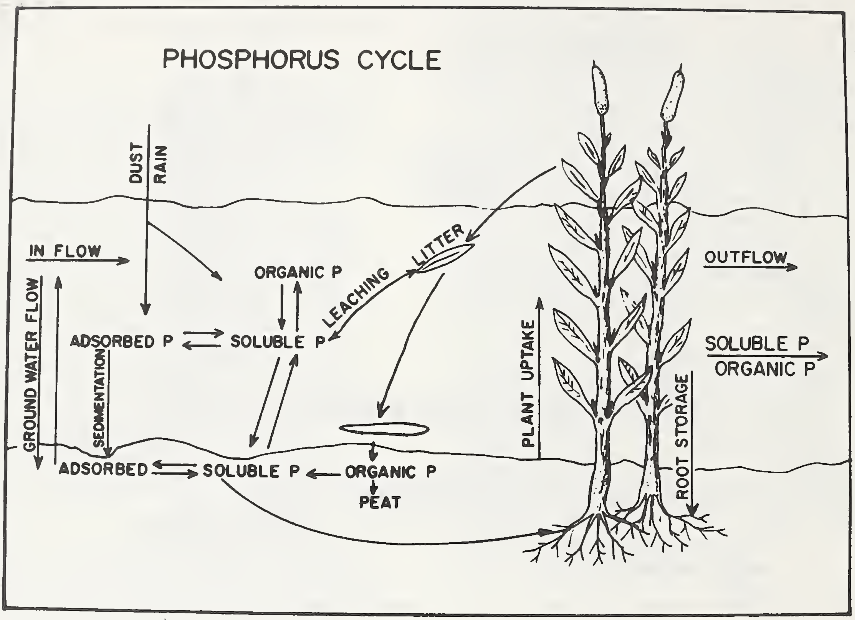

Figure 2.--The phosphorus cycle in a wetland.

not available to plants and P included in organic matter that accumulates in wetlands. Monitoring of wetlands used for waste water treatment has shown that removal of waste water N and P is most efficient at low N and P loading rates (Nichols 1983).

PESTICIDE TRANSFORMATION

Most pesticides enter wetlands as organic compounds in solution or adsorbed on sediments (fig. 3). Pesticides adsorbed on sediments are deposited at the bottom of the wetland and begin degradation. As water flows through vegetation, pesticides in solution may be adsorbed by plant litter or on the foliage of growing plants. These pesticides also begin to degrade. Some pesticides maybe taken up by plants and either degraded within the plant or returned to the system when the plant material decomposes. Since most of the pesticides in use today are not persistent, detention in wetlands due to sedimentation, plant uptake, adsorption on vegetation and litter, and reduced flow velocities should result in considerable pesticide degradation in wetlands. Pesticides generally would not be expected to move through wetlands except in those cases where pesticides enter the wetland in solution and water moves through well defined channels at high velocities.

MODELING CONCEPTS

Concepts for modeling the physical, chemical, and biological reactions occurring in wetlands are in the early states of development. A few ideas will be mentioned to suggest areas where concepts from other models might be applied to a wetlands submodel.

Since the wetlands submodel will be an integral part of SWAM, inputs for water flow into the wetlands submodel will be supplied from the hydrologic components of SWAM. Probably, the flow through the wetland could be modeled by considering two main cases: (1) sheet flow and

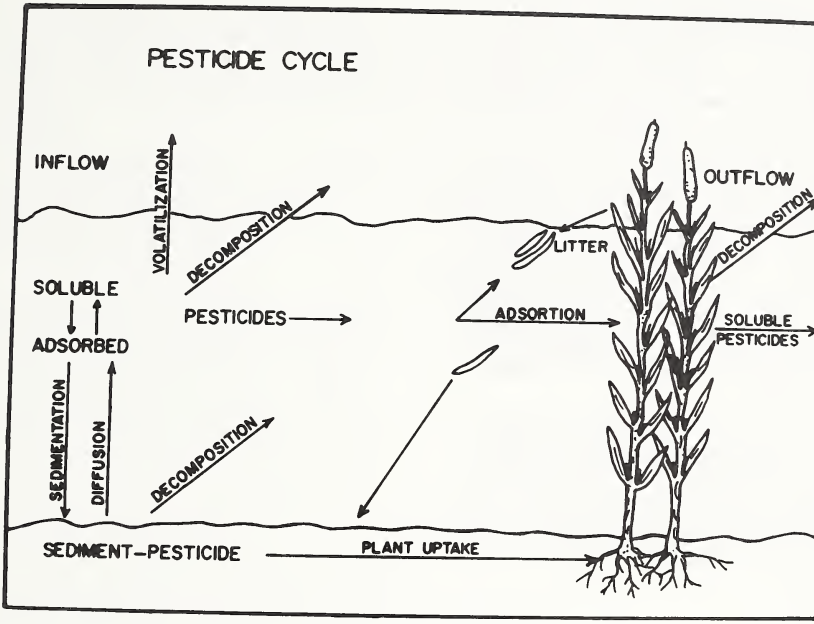

Figure 3.--The pesticide cycle in a wetland.

(2) channel flow subject to frequent overflow into surrounding vegetated areas. Many of the concepts used in the SWAM reservoir model probably can be adapted for the first case, while some of the concepts used in modeling stream flow can be adapted for the second case. Another possibility is to use a form of the Manning equation to describe sheet flow in wetlands. Hopefully, groundwater flow can be described using many of the same concepts used in SWAM groundwater submodel. After the flow velocity has been modeled, the same concepts used to describe sedimentation in stream channels and reservoirs can be applied to the wetlands submodel.

Vegetative production could be modeled by developing a plant growth curve for wetland plants similar to the ones used in the Erosion Productivity Impact Calculator (EPIC) model. Plant uptake of N and P could also be described in the same manner as in the EPIC model except that equations for P availability would have to be modified to account for the increased P availability in anaerobic sediments.

It may be possible to adapt many of the equations for N transformations in the Chemicals, Runoff, and Erosion of Agricultural Management Systems (CREAMS II) model for use in the wetlands submodel. Some additional work would be required to determine mineralization rates in wetlands. The denitrification subroutines in CREAMS II could be modified to account for the high organic matter levels in wetlands. The detention time in anaerobic zones would determine the amount of denitrification. Finally, many of the same concepts used to describe pesticide transformations in streams and reservoirs probably can be adapted for the wetlands submodel.

RESEARCH NEEDS

The information on the hydrology and biology of wetlands is quite sparce. Some examples of the research needs in hydrology are a better understanding of sheet flow through wetlands, an understanding of groundwater - surface water interactions in wetlands, and better ways to estimate the storage capacities of the different types of wetlands. To understand nutrient transformations, more information on mineralization rates, denitrification rates, and nitrogen fixation rates in a wide variety of wetland ecosystems is needed. More information on sediment phosphorus availability under flooded conditions and better estimates of primary productivity by different vegetative systems in the various climatic zones are needed. More information on pesticide adsorption and uptake by aquatic vegetation and on pesticide degradation rates in aquatic systems is needed. To secure these kinds of information, wetlands problems must be addressed by interdisciplinary teams including biologists, hydrologists, chemists, and soil scientists.

Although the information needed to develop a wetlands submodel is limited, most of the same physical, chemical, and biological reactions occurring in wetlands have been described in lake and watershed models. Hopefully, by using the limited data and information available on wetland ecosystems and adapting concepts from other models, a reasonably accurate wetlands submodel can be developed.

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SCE RESPONSE - CHEMICAL AND BIOLOGICAL PANEL

Carl H. Thomas[1]

Most of the Soil Conservation Service (SCS) participants in this session are biologists. Therefore, our primary interest is in the biological and chemical processes taking place in streams, lakes, and wetlands. This interest can be expressed as offsite effects of land use and management on aquatic organisms.

We were very interested and enthusiastic about the models and modeling approaches which concerned the hydrology of wetlands and its relationship to nutrients and pesticides. In fact, the tracking of nutrients and pesticides downstream or in the channel system was of great ineterst.

Of course, the fate of pesticides under different land management systems, such as no-till, relates directly to wildlife habitat and the well-being of various wildlife species. Sediment transport in streams is of great interest to the biologists also. There is a continuing need to predict or estimate offsite impacts of soil and water conservation measures on fish habitat. Any effort in modeling should link the physical and chemical condition to the biological components of the aquatic habitat.

We can see the value of such models as discussed. They will help us greatly in environmental evaluations and our efforts to predict impacts on the fish and wildlife resources.

We were somewhat concerned about the complex input data required by models. Input data must be readily available to field people, and evaluation periods should be kept as short as possible.

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MODEL DEVELOPMENT PRIORITIES AND RESEARCH NEEDS - SOIL-WATER-PLANT RELATIONSHIPS, AN SCS OVERVIEW

Allen R. Hidlebaugh[1]

SCS needs crop models and is vitally interested in their development and validation. From the SCS perspective, the order of priority crop-modeling research should be to develop models that will--

1. Assess the impact of sheet and rill erosion and wind erosion on crop yields. The Erosion Productivity Impact Calculator (EPIC) model and the Productivity Index (PI) soil vulnerability approach are addressing this need.

2. Assess the impact of concentrated flow (ephemeral gully) erosion on crop yields.

3. Assess the impact of conservation tillage on crop yields.

4. Assess the impact of level, closed-end terraces on crop yields in the Great Plains.

5. Improve irrigation scheduling.

6. Assist in the development of crop production systems for areas with limited water supplies.

7. Assist our cooperators (farmers and ranchers) in making crop management decisions, for example, amounts and timing of applications of fertilizer, pesticides, and other chemicals.

If we in SCS are to be of assistance in the development and validation of crop models, we have a few questions for the modelers:

1. What are the limiting soil characteristics for crop growth? For example, limiting factors in the PI approach used in the Corn Belt included pH, bulk density, available water capacity, and a weighting factor for rooting depth.

2. What kinds of soil characterization data (laboratory and field observations) are the critical parameters that SCS can provide to modelers, with emphasis on those we are not already providing? For example, we can provide rooting depth observations by kind of soil and by specific crops for each soil pedon sampled for characterization at the National Soil Survey Laboratory. We can also provide data on the soil landscapes (slope, aspect, and runoff or runon position).

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CONCURRENT SESSION II - SOIL-WATER-PLANT RELATIONSHIPS, AN ARS OVERVIEW

Albert R. Grable[1]

During the past two and one-half days we have heard presentations on each of the major models being designed for evaluating or managing our natural resource base. Those presentations included the background and philosophy of modeling soil-water-plant relationships. The major purpose of this session is to explore ways that modeling of crops and soils can contribute to modeling of natural resources, mainly for meeting the SCS needs that Al Hidlebaugh presented. Modeling for forecasting crop yields, understanding specific plant processes, or other purposes are of secondary interest for this symposium.

During the first afternoon, the speakers will discuss in detail their use and treatment of crop and soil submodels in CREAMS, EPIC, and the other resource models listed on the agenda. They will provide information about strengths, weaknesses, size of area considered, time steps, commodities, data needs, and topics they feel are important. The speakers will indicate future directions and research needs.

During the following morning, the first group of speakers will present in detail the current status of crop and soil models. Those speakers will be followed by three panels on the special topics of water relations, interfacing models of different kinds, and use of remotely sensed data. These speakers and panels also will discuss strengths, weaknesses, scale, data needs, and other relevant information for determining future directions and research needs.

During the last afternoon of this session, we need to synthesize all the information presented at these meetings and identify those areas in which crop modelers can help the resource modelers (or vice versa). Consider such topics as coordination of research and development efforts, SCS research needs, tasks to be accomplished, and needed data sets. We will break into three separate work groups on water, soils, and crops chaired by Jerry Hatfield, Wayne Willis, and Betty Klepper, respectively. Join the group of greatest interest to you. Each group should identify research needs, potential obstacles, and opportunities for cooperative work. On the agenda are listed topics such as runoff, erosion, and biomass which can be used as a checklist. Keith Saxton has agreed to be our reporter at the plenary session on Friday morning, so give him all the help you can.

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CREAMS2 PLANT GROWTH SIMULATION

R. E. Smith[1]

CREAMS2 uses a mechanistic general plant model which can be used for either annual or perennial crops, and it responds to grazing, harvest, and stresses in a generally realistic manner.

In general the model can be expressed as

$$\Delta pm = C_e \cdot F_e \cdot F_s \cdot F_m \cdot S \cdot R \cdot \Delta t \qquad (1)$$

in which

Δpm = incremental production of plant material in time Δt; kg/ha,

C_e = photosynthetic conversion coeffi cient for production of plant material from radiant energy, kg/ha/Langley/day

F_e = energy conversion efficiency factor,

F_s = plant age factor, varies from 0 to 1,

F_m = plant size factor, varies from 0 to 1,

S = stress factor, considering temperature, water, and nutrient stresses; from 0 to 1,

R = daily radiation in Langleys,

Δt = time increment.

C_e is a crop-dependent parameter, with some plants being more efficient than others. F_s is described in figure 1, and F_m is described in figure 2. The stress factor is the minimum of water, temperature, and nutrient stresses. The water stress factor is 1 for soil water content down to a water content which is 20 percent greater than the 15-bar water content, (θ_{15}), and it declines linearly to 0 at θ_{15}. The nutrient stress factor is a function of the ratio of the actual nitrogen use and potential nitrogen use. Potential N use is found from the relation between plant N-content and growth stage (fig. 3). The plant N-content relation is described by three parameters, including N-contents at emergence and maturity. This part of the plant model has also been used in EPIC (Williams et al. 1982).

If root zone soil nitrate is insufficient to meet the accumulated demand thus calculated, the nitrogen stress factor τ_n is calculated (Williams et al. 1982) as

$$\tau_n = 2\,\frac{\text{actual N use}}{\text{potential N use}} - 1$$

Plants are assumed to be able to selectively garner N, if available, in quantity greater than that which would be taken in by roots if root uptake water were that of the root zone soil water.

Temperature stress factor τ_r is a dimensionless function of a minimum growth temperature, T_b, and an optimum growth temperature, T_{op}, and is illustrated in figure 4. Several types of general curves are candidates, and plants naturally differ. The lower τ_r function with a = 1.5 is used in CREAMS2. T_* in this figure is defined on the abscissa.

F_e is a function of leaf area index and increases with leaf area. It expresses indirectly a self-dependent growth rate. Plant material produced by the model thus described is divided among leaf/stalk, roots, and fruit/seed material according to the plant's age and relative size. Presently, a general relationship is used for all plants, as illustrated in figure 5. Relative root/leaf ratio is a function of relative size (lower scale) and relative seed/fruit weight is a function of relative age in degree days (see Williams et al. 1982).

The major parameters needed to describe a plant thus include the following:

1. age in degree-days to onset of senescence,
2. age at emergence in degree-days (from planting for annuals, and from January 1 for perennials),
3. potential total plant material production for no stress (s=1),
4. N-content with growth stage,
5. relative weight of fruit/seed at maturity,
6. maximum normal rooting depth,
7. photosynthetic energy conversion efficiency factor.

Figure 6 illustrates the plant model simulation of a hypothetical corn crop, with no nutrient limits imposed.

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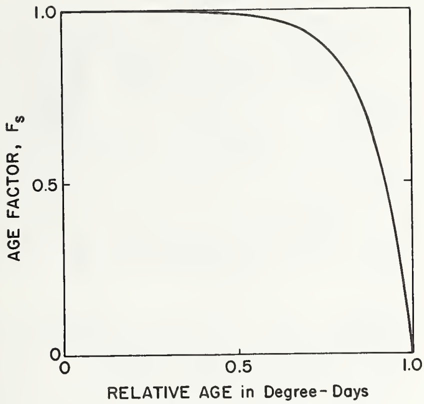


Figure 1.--Plant growth rate modification due to age in degree-days.

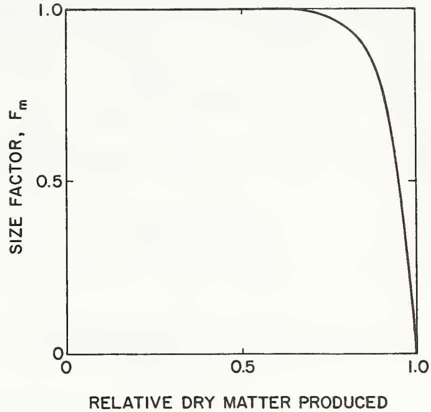


Figure 2.--Plant growth rate modification due to relative mass.

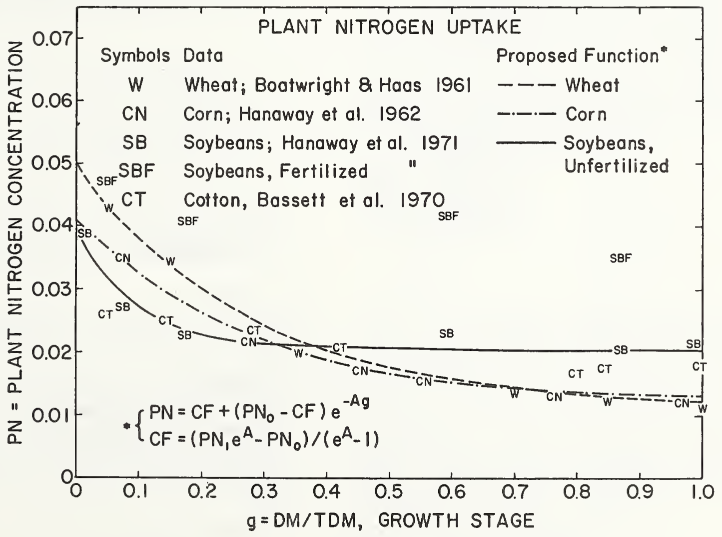
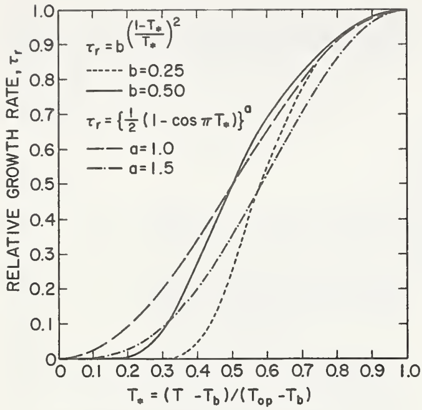


Figure 3.--Plant requirement for N (and P) is found from a relation between N content and relative plant size or growth stage. PN_0 is N content of g = 0, and PN is mature N content.



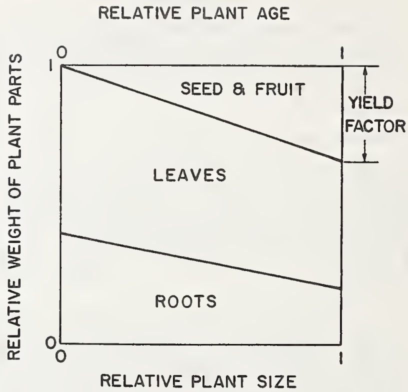


Figure 4.--Several functions can be used to describe the effect that temperature has on plant growth. Here, T_b is temperature below which no growth occurs, and T_{op} is optimum growth temperature. The curves are all symmetrical about the line $T_* = 1.0$.

Figure 5.--Plant mass produced during growth is divided among leaf/stems, roots, and fruits/seeds according to both plant relative age and relative size.

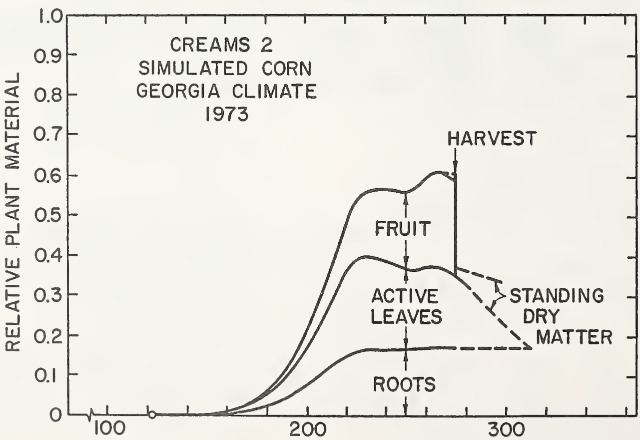


Figure 6.--A simulated corn crop when grown in an actual rain sequence in a relatively dry year produces about 70 percent of its potential corn

EPIC CROP GROWTH MODEL

J. R. Williams and C. A. Jones[1]

INTRODUCTION

The EPIC crop growth model was developed for simulating the effects of erosion on crop yield. Thus, the model must be sensitive to changes in plant environment like climate, nutrient supply, and soil characteristics. The processes simulated include energy interception; energy conversion to biomass; division of biomass into roots, aboveground biomass, and seed; root growth and sloughing; water use; and nutrient uptake. Potential plant growth is simulated daily and constrained by the minimum of four stress factors (water, nitrogen, phosphorus, and temperature). Root growth is also constrained by the minimum of four stress factors (soil strength, temperature, aluminum toxicity, and aeration). Thus, as erosion removes top soil, the effect on crop production is expressed in these stress factors.

A single model is used in EPIC for simulating all the crops considered (corn, grain sorghum, wheat, barley, oats, sunflowers, soybeans, alfalfa, cotton, peanuts, and grasses). Of course, each crop has unique values for the model parameters. EPIC is capable of simulating crop growth for both annual and perennial plants. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops (alfalfa and grasses) maintain their root systems throughout the year, although the plant becomes dormant after frost. They start growing when the average daily air temperature exceeds the base temperature of the plant.

POTENTIAL GROWTH

Energy interception is estimated with the equation

$$PAR = 0.02092\,(RA)\Big(1. - \exp(-0.65(LAI + 0.05))\Big) \quad (1)$$

where PAR is the photosynthetic active radiation in MJ m^{-2}, RA is solar radiation in ly, and LAI is the leaf area index. The potential increase in biomass for a day can be estimated with the equation

$$\Delta B_p = (BE)\,(PAR)\,(\frac{HRLT}{12})^3\,(1 + \frac{\Delta HRLT}{\Delta t})^2 \quad (2)$$

where ΔB_p is the daily potential increase in biomass in kg ha^{-1}, BE is the crop parameter for converting energy to biomass in kg MJ^{-1}, HRLT is the daylight time during a 24-h period in h, and and $\Delta HRLT/\Delta t$ is the change in daylight time during a 24-h period. The daylight time is a function of the time of year and latitude as expressed in the equation

$$HRLT = 7.64 \cos^{-1}\left(\frac{-\sin(\frac{2\pi}{360}LAT)\sin(SD) - 0.044}{\cos(\frac{2\pi}{360}LAT)\cos(SD)}\right) \quad (3)$$

where LAT is the latitude of the watershed in degrees and SD the sun's declination angle is defined by the equation

$$SD = 0.4102 \sin(\frac{2\pi}{365}(IDA - 80.25)) \quad (4)$$

where IDA is the day of the year. The LAI, a function of biomass, is estimated with the relationships

$$LAI_{IDA} = \frac{(LAI_{mx})\,(WLV)_{IDA}}{WLV_{IDA} + 5512 \exp(-0.000608\ WLV)_{IDA}}, \quad B_{1,IDA} \leq DLAI \quad (5)$$

$$LAI_{IDA} = LAI_o\left(\frac{1 - B_{1,IDA}}{1 - DLAI}\right)^2, \quad B_{1,IDA} > DLAI \quad (6)$$

where LAI_{mx} is the maximum LAI potential for the crop, WLV is the aboveground biomass minus yield in kg ha^{-1} on day IDA, B_1 is the fraction of the growing season, DLAI is the fraction of the growing season when LAI starts declining, and LAI_o is the LAI value from equation 5 when B_1 = DLAI. The value of WLV is computed daily using the equation

$$WLV = Bp - RWT - YLD \quad (7)$$

where RWT is the root weight in kg ha^{-1} and YLD is the portion of the plant used in producing yield. The daily fraction of the potential increase in biomass partitioned to yield is computed with the equation

$$\Delta YLD = \frac{(\Delta Bp)\,(B_1)}{0.8\ GK} \quad (8)$$

$$YLD \leq \frac{Bp}{GK} \quad (9)$$

where GK is the ratio of total biomass to crop yield under favorable growing conditions. The dimensionless biomass variable B_1 acts as a weighting function in equation 8--early in the growing season little of the biomass is partitioned into yield because B_1 is small. As the growing season progresses, however, more and more weight is given to the yield component of the biomass. For this reason, late season stresses reduce yields more than early season stresses. The amount of root growth for a day is estimated with the equation

$$\Delta RWT = \Delta Bp\ (0.4 - 0.2\ B_1) \quad (10)$$

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Daily root sloughing is estimated with the equation

$$\Delta RWS = 0.1\,(\Delta B_p)\,(B_l) \tag{11}$$

where ΔRWS is the amount of root sloughing during a day in kg ha^{-1}. The change in root weight through the root zone is simulated as a function of plant water use and accumulated root weight in each soil layer using the equation

$$RW_i = RW_{oi} + (\Delta RWL)\,(RWF)_i \tag{12}$$

where RW_o and RW are the root weights in soil layer i at the start and end of a day in kg h^{-1}, ΔRWL is the change in live root weight during a day in kg ha^{-1}, and RWF is a root weight distribution factor. The daily change in live roots is computed by subtracting the sloughed roots from the total root growth

$$\Delta RWL = \Delta RWT - \Delta RWS \tag{13}$$

The root weight distribution factor is determined by considering the sign of ΔRWL.

$$RWF = u_i / \sum_{i=1}^{M} u_i, \quad \Delta RWL > 0 \tag{14}$$

$$RWF = RW_i / \sum_{i=1}^{M} RW_i, \quad \Delta RWL < 0 \tag{15}$$

Equations 14 and 15 simply distribute root growth as a function of water use if the root weight is increasing and as a function of existing root weight if root weight is decreasing. Rooting depth is simulated as a function of heat units and potential root zone depth.

$$\Delta RD = 2(RZ)\,(HU) / PHU, \quad RD \le RZ \tag{16}$$

where ΔRD is the potential daily change in crop root depth in mm.

GROWTH CONSTRAINTS

The potential biomass predicted with equation 2 is adjusted daily if one of the plant stress factors is less than 1.0 using the equation

$$\Delta B = (\Delta B_p)\,(REG) \tag{17}$$

where REG is the crop growth regulating factor (the minimum stress factor). The water stress factor is computed by considering supply and demand in the equation

$$WS = \frac{E_p}{\sum_{i=1}^{M} u_i} \tag{18}$$

where WS is the water stress factor (0 to 1). The value of E_p is predicted in the evapotranspiration model, and u_i is a function of depth and soil water content.

$$u_{pi} = RGF^{0.5}\left(\left(\frac{E_p}{1-\exp(-\Lambda)}\,0.5 - \exp\left(-\frac{\Lambda Z_i}{RZ}\right) + 0.5\exp\left(-\frac{\Lambda Z_{i-1}}{RZ}\right)\right) - 0.5\sum_{j=1}^{i-1} u_j\right) \tag{19}$$

where u_{pi} is the potential water use rate from layer i in mm d^{-1}, RGF is the root growth stress factor (0-1), Z is the depth to the bottom of soil layer i, and Λ is a use rate-depth parameter. The details of evaluating Λ are given by Williams and Hann (1978). The value of Λ used in EPIC (3.065) was determined assuming that about 30 percent of the total water use comes from the top 10 percent of the root zone under ideal conditions. Equation 19 allows roots to compensate for water deficits in certain layers by using more water in layers with adequate supplies. The potential water use must be adjusted for water deficits to obtain the actual use for each layer.

$$u_i = u_{pi}, \quad SW_i > 0.25\,FC_i \tag{20}$$

$$u_i = u_{pi}\left(\frac{SW_i}{0.25\,FC_i}\right), \quad SW_i \le 0.25\,FC_i \tag{21}$$

where SW is the soil water content in layer i in mm and FC is the field capacity water content in mm. Note that the actual use for the layers above the i^{th} layer in equation 19 must be known. This presents no problems, however, since $u_i = 0$ when i = 1.

The temperature stress factor is computed with the equation

$$TS = \exp\left(\Omega\left(\frac{T_o - T}{T}\right)^2\right) \tag{22}$$

where TS is the temperature stress factor (0 to 1), Ω is the temperature stress parameter for the crop, T_o is the optimal temperature for the crop in °C, and T is the daily average air temperature in °C. The stress parameter is evaluated by appropriate substituting and rearranging of equation 22

$$\Omega = \frac{\ln(0.9)}{\left(\dfrac{T_o - \dfrac{T_o + T_b}{2}}{\dfrac{T_o + T_b}{2}}\right)^2} \tag{23}$$

where T_b is the base temperature for the crop in °C. equation 23 sets TS = 0.9 when the air temperature is half way between T_b and T_o.

The N and P stress factors are based on the ratio of accumulated plant N and P to the optimal values. The stress factors vary nonlinearly from 1.0 at optimal N and P levels to 0 when N or P is half the optimal level. In the case of N, the scaling equation is

$$SN_{S,IDA} = 2\left(1 - \frac{\sum_{j=1}^{IDA} UN_j}{(c_{NB})_{IDA}(B)_{IDA}}\right) \tag{24}$$

where $SN_{S,IDA}$ is a scaling factor for the N stress factor, c_{NB} is the optimal N concentration of the crop on day IDA, B is the accumulated biomass in kg ha^{-1}, and UN is the crop N uptake on day j in kg ha^{-1}. The N stress factor is computed with the equation

$$SN_{IDA} = 1 - \frac{SN_{S,IDA}}{SN_{S,IDA} + 29.534 \exp(-10.93\ SN_{S,IDA})} \tag{25}$$

where SN_{IDA} is the N stress factor for day IDA. Equations 24 and 25 allow SN to range from 0.0, when the ratio $UN/(c_{NB} \cdot B)$ is equal 0.5, to 1.0, when the ratio is 1.0. The P stress factor is computed with equations 24 and 25 written in P terms. Finally, the value of REG is determined as the minimum of WS, TS, SN, and SP. REG is used to adjust YLD, RWT, and RWL with equations similar to equation 2.

The root growth stress factor is the minimum of stresses caused by soil strength, temperature, aluminum toxicity, and aeration. Temperature stress for each soil layer is computed by substituting soil temperature for air temperature in equation 22. Stress caused by poor aeration is estimated with the equations

$$AS_i = \exp(23.\ (0.85 - SWF_i)), \quad SWF_i > 0.85 \tag{26}$$

$$AS_i = 1.0, \quad SWF_i \leq 0.85 \tag{27}$$

where AS is the aeration stress factor in layer i and SWF, the soil water factor, is the ratio of soil water to porosity. Stress from soil strength is estimated as a function of soil texture and bulk density using the equation

$$SS_i = 0.1 + \frac{0.9\ BDP_i}{BDP_i + \exp(bt_1 + (bt_2)(BDP_i))} \tag{28}$$

where SS is the soil strength factor in layer i, BDP is the soil bulk density in t m^{-3}, and bt_1 and bt_2 are parameters dependent upon soil texture. The values of bt_1 and bt_2 are obtained from a simultaneous solution of equation 28 by substituting boundary conditions for stress. The lower boundary where essentially no stress occurs is given by the equation (Jones 1983)

$$BD_1 = 1.15 + 0.00445\ SAN \tag{29}$$

where BD_1 is the bulk density that gives no stress (SS = 1) for a particular percent sand, SAN. The upper boundary is given by the equation (Jones 1983)

$$BD_2 = 1.5 + 0.005\ SAN \tag{30}$$

where BD_2 is the bulk density that gives SS ~ 0.2 for a particular percent sand, SAN. The equations for estimating bt_1 and bt_2 are

$$bt_2 = \frac{\ln(0.112\ BD_1) - \ln(8.\ BD_2)}{BD_1 - BD_2} \tag{31}$$

$$bt_1 = \ln(0.0112\ BD_1) - (bt_2)(BD_1) \tag{32}$$

Equations 31 and 32 assure that equation 28 gives SS values of 1.0 and 0.2 for BDP equal BD_1 and BD_2.

Root growth stress caused by aluminum toxicity is estimated with the equation

$$ATS_i = \frac{100 - ALS_i}{100 - ALO}, \quad ALS_i > ALO \tag{33}$$

$$ATS_i = 1, \quad ALS_i \leq ALO \tag{34}$$

where ATS is the aluminum toxicity root growth stress factor for soil layer i, ALS is the aluminum saturation in percent, and ALO is the maximum ALS value a crop can tolerate without stress in percent. Crop specific values of ALO are determined from the equation

$$ALO_j = 10 + 20\ (ALT_j - 1) \tag{35}$$

where ALT_j is the aluminum tolerance index number for crop j. Values of ALT range from 1 to 5 (1 is sensitive; 5 is tolerant) for various crops.

Finally, the root growth stress factor, RGF, is the minimum of AS, SS, ATS, and TS. Besides constraining water use as defined in equation 19, RGF also constrains rooting depth. Combining RGF with equation 16 gives

$$\Delta RD = 2\ (RZ)(HU)(RGF) / PHU, \quad RD \leq RZ \tag{36}$$

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MODELING TILLAGE AND SURFACE RESIDUE EFFECTS ON SOIL TEMPERATURE, SOIL HEAT FLUX, CORN EMERGENCE, AND PLANTING DATES[1]

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INTRODUCTION

Soil temperature influences on seed germination, plant root and top growth, nitrogen transformations, insect and weed dynamics, and degradation of herbicide and pesticide are well recognized in the literature. Increased use of conservation tillage and integrated pest management necessitates a knowledge of soil temperatures and other soil physical parameters for exploring management alternatives that maximize crop production, reduce soil erosion, and save energy. In these schemes, dates of planting, fertilization, and other chemical applications are strongly influenced and, in some cases, set by soil temperature in the upper 0.30 m of the profile. Since reduced tillage usually increases the surface residue cover and changes the soil thermal regime, some of these management alternatives would vary with the type of conservation tillage.

The effect of crop residues on the heat balance of soil profiles depends largely on the quantity, type, and placement of these residues. Generally, surface residues depress the soil temperatures at the seed zone depth by (1) acting as an insulating layer and (2) reflecting a greater fraction of solar radiation back to the atmosphere. Depressed seed zone temperatures have often been related to a delay in seed germination, slow corn seedling growth, and reduced yield of corn in areas with cool and wet springs, such as the northern Corn Belt. A review by Willis and Amemiya (1973) details the effects of tillage on soil temperature and their interactions with growth of various crops.

The objective of this paper is to (1) discuss models that include the effects of soil disturbance and change in surface residue during tillage on soil temperature, soil heat flux, and corn emergence and (2) present a model to calculate probabilities of time to corn emergence at various planting dates under two tillage and residue conditions for the northern Corn Belt.

ROOT ZONE SOIL TEMPERATURE MODELS

Most root zone temperature models are based on the finite difference or Fourier series solution of the partial differential equation describing heat flow in soils:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right) \qquad (1)$$

where T is temperature, t is time, z is depth and κ is thermal diffusivity.

Finite Difference Model

Equation [2] is a finite difference approximation of equation 1:

$$\frac{T_{i,j}-T_{i,j-1}}{\Delta t} = \frac{(T_{i-1,j}-T_{i,j})\kappa_{i-1/2,j}}{\Delta z^2} - \frac{(T_{i,j}-T_{i+1,j})\kappa_{i+1/2,j}}{\Delta z^2} \qquad (2)$$

where i refers to depth and j refers to time. Equation 2 when written for each depth, results in a tridiagonal matrix that can be solved for root zone temperatures if initial and boundary temperatures are known. For most simulations, the soil profile can be assumed to be deep; hence, soil temperature at the lower boundary is constant.

To include the effects of tillage and surface residues in the upper boundary and root zone soil temperature models, Gupta et al. (1983) suggested normalizing the soil temperature ($T_{z,t}$) with respect to daily maximum ($T_{o,sx}$) and minimum ($T_{o,sn}$) soil surface temperatures using equation 3.

$$\Gamma_{z,t} = \frac{T_{z,t} - T_{o,sn}}{T_{o,sx} - T_{o,sn}} \qquad (3)$$

Hourly normalized values were then further averaged ($\Gamma^*_{z,t}$) over a given season using equation 4:

$$\Gamma^*_{z,t} = \frac{1}{N}\Sigma\Gamma_{z,t} \qquad (4)$$

where N is the number of days in the season.

Gupta et al. (1981, 1982, 1983) discussed procedures to calculate upper boundary temperatures for different tillage and surface residue conditions. One of these procedures used equation 5 to estimate hourly upper boundary temperatures:

$$T_{o,t} = \Gamma^*_{o,t}(T'_{o,sx} - T'_{o,sn}) + T'_{o,sn} \qquad (5)$$

where $\Gamma^*_{o,t}$ is the average normalized temperature at the soil surface and $T'_{o,sx}$ and $T'_{o,sn}$ are estimated maximum and minimum soil surface temperatures for a given tillage and surface residue condition. Gupta et al. (1983) presented diurnal curves of $\Gamma^*_{o,t}$ for various tillage and surface residue covers during fall, spring, and summer. These curves were approximately the same for all treatments over all seasons. Gupta et al. (1983) suggested using one of these curves

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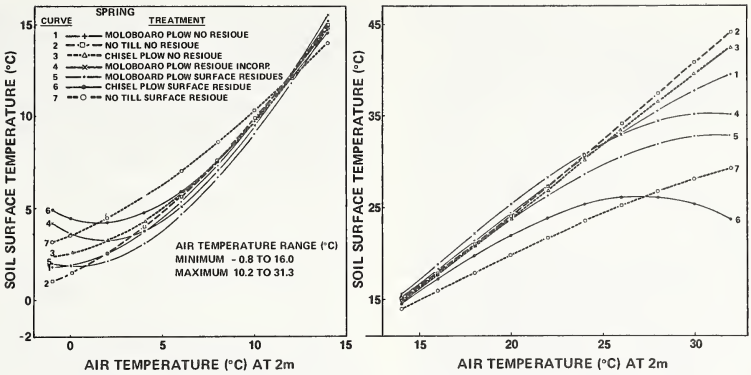

Figure 1.--Daily maximum and minimum temperatures of air (2-m height) plotted versus soil surfaces temperature for various tillage and surface residue cover combinations during spring, 1982.

for the value of $\Gamma^*_{o,t}$ in equation 5. Figure 1 shows the relationship between daily maximum and minimum soil surface temperatures and daily maximum and minimum air temperatures during spring. These curves could be used to estimate $T'_{o,sx}$ and $T'_{o,sn}$ from daily maximum and minimum air temperatures. Similar curves for other seasons and their corresponding regression equations have been given by Gupta et al. (1983). Although curves in figure 1 and regression equations of Gupta et al. (1983) were obtained using the experimental data from Morris and St. Paul, MN, preliminary tests by the authors showed that these curves could be extended to States surrounding Minnesota (ND,SD, IA, WI). Efforts are underway to develop similar curves for at least one location in each of the regions of the United States.

Fourier Series Model

If average normalized soil temperature at the soil surface ($\Gamma^*_{o,t}$) is an arbitrary periodic function of time with a radial frequency ω, it can be represented by a Fourier series with radial frequencies that are integral multiples of ω. Using the soil temperature data base from Morris and St. Paul, MN, Gupta et al. (1984) evaluated the Fourier coefficients for different tillage and surface residue conditions over four seasons. Analysis showed that amplitude and phase angles of the first two harmonics were approximately the same for all treatments over all seasons for any given depth. Thus, average values of these coefficients representing all treatments and all seasons were estimated for the generalized Fourier series model described as

$$\Gamma^*_{z,t} = a\,e^{bz} + 0.392\,e^{-z/D_1} \sin(\omega t + 3.92 - z/D_1) + 0.119\,e^{-z/D_2} \sin(2\omega t + 0.62 - z/D_2) \qquad t = 0,1,\ldots 23 \tag{6}$$

$$\text{where } D_1 = \sqrt{2\kappa/\omega} \tag{7}$$

$$\text{and } D_2 = D_1/\sqrt{2} \tag{8}$$

Coefficients a and b are empirical constants and D_1 and D_2 are damping depths corresponding to first and second harmonics.

Values of a and b for various seasons can be obtained from table 3 of Gupta et al. (1984). Equation 6 assumes that κ is constant with depth and time. Equation 6 can also be used to estimate values of $\Gamma^*_{o,t}$ for use in equation 5. Average normalized hourly soil temperatures estimated from equation 6 can now be converted to real soil temperatures using equation 9 and the estimates of daily maximum and minimum soil surface temperature (figure 1):

$$T_{z,t} = \Gamma^*_{z,t}\,(T'_{o,sx} - T'_{o,sn}) + T'_{o,sn} \tag{9}$$

Values of $\Gamma^*_{z,t}$ were approximately the same for all treatments in any season.

SOIL HEAT FLUX MODEL

Heat flux at the soil surface is often needed in the calculation of evaporation using the energy balance method. The net daily soil heat flux varies between 10 to 15 percent of the total net radiation. Because of relatively small magnitude and the difficulties of measuring or estimating soil heat flux, scientists have generally ignored soil heat flux in the calculations of evaporation. Gupta et al. (1984) derived an expression to calculate soil surface heat flux from equation 6:

$$Q^*_{o,t} = -C[a\,b - 0.392\sqrt{\kappa\omega}\,\mathrm{Sin}\,(\omega t + 3.92 + \pi/4) - 0.119\sqrt{2\,\kappa\omega}\,\mathrm{Sin}\,(2\omega t + 0.62 + \pi/4)] \tag{10}$$

where $Q^*_{o,t}$ is the soil heat flux calculated using the normalized soil temperatures, and C is the volumetric heat capacity. Equation 10 can now be converted from normalized soil heat flux to real heat flux using equation 11:

$$Q_{o,t} = Q^*_{o,t} \quad (T'_{o,sx} - T'_{o,sn}) \qquad (11)$$

PROCEDURES

Soil Temperatures

The data used in the development of the Fourier series soil temperature model were gathered at the University of Minnesota Experimental Station at Rosemount, MN. The soil is a Waukegan silt loam (Typic Hapludoll). Details of the experimental set-up are described by Gupta et al. (1983). Briefly, the tillage and surface residue treatments along with percent residue cover and random roughness (mm) were as follows:

1. moldboard plow with no residues (MPNR), 0 percent, 9.0
2. chisel plow with no residues (CHNR), 9 percent, 10.0
3. no-till no residues (NTNR), 25 percent, 4.0
4. moldboard plow with partially incorporated residues (MPRI), 3 percent, 9.0
5. chisel plow with partially incorporated residues (CHRI), 40 percent, 10.0
6. moldboard plow with surface residues (MPSR), 38 percent, 9.0
7. chisel plow with surface residues (CHSR), 41 percent, 10.0
8. no-till surface residues (NTSR), 75 percent, 4.0

Percent residue cover was measured at planting during 1981. Higher percent residue cover (25 percent) on the NTNR treatment was mainly due to stubble left from the previous crop. Residue coverage in NTNR plot between the stubble rows was nearly absent. Soil temperatures were measured hourly with copper-constantan thermocouples placed just under the soil surface, and at 0.05-, 0.10-, and 0.30-m depths. During summer, thermocouples were placed in the corn (Zea mays L.) row, whereas during fall and spring, thermocouples were placed in between the rows. Details of the residue measurement technique and thermocouple placement have been described in the earlier publication (Gupta et al. 1983).

Corn Emergence

During 1983 a detailed study of soil temperature effects on corn emergence was undertaken at the Rosemount Experiment Station. Corn was planted on 10 May 1983 using a John Deere Max-Emerge planter. Soil temperature at the seed zone depth (5 cm) was monitored hourly with the data acquisition system. Daily counts of total number of corn plants emerged per 3.05 m of row were recorded at four locations in each of the tillage-residue plots. Residue cover at planting corresponded to 4.0, 8.3, 30.0, 12.7, 34.0, 56.3, 59.0, and 75.0 percent for MPNR, CHNR, NTNR, MPRI, CHRI, MPSR, CHSR, and NTSR treatments, respectively. Since corn planting was between rows of the previous year's crop in NTNR treatment, corn seed and thermocouple in this treatment were under bare soil surface conditions. Growing degree days (GDD) were calculated from the hourly soil temperature at the 5 cm depth using equation 12:

$$GDD = \Sigma(T_i - 10)/_{24} \qquad 10 < T_i < 30 \qquad (12)$$

RESULTS AND DISCUSSIONS

Prediction of Root Zone Soil Temperature

Gupta et al. (1984) made an independent check of Fourier series (equation 6) and finite difference models using the air and soil temperature data (U.S. Department of Commerce, 1980) from Waseca, MN for 45 days during the spring of 1980. Gupta et al. (1984) assumed a constant thermal diffusivity (0.44 mm^2 s^{-1}) with depth and time for both Fourier series and finite difference solutions. Comparisons between predicted (Fourier series) and measured soil temperatures at 0.05- and 0.10-m depth are shown in figures 2 and 3, respectively. Predicted temperatures correspond to the NTNR treatment. Figures 2 and 3 show that predicted temperatures were close to the measured values except for a few days. Statistical comparison of the Fourier series and the finite difference models indicated a greater variation in the predicted temperatures from the Fourier series solution. The advantages of Fourier series equation (equation 6) over finite difference method are its simplicity and ease of solution on a hand calculator. Limitations of equation 6 are (1) in the nonconstancy of $\bar{\Gamma}^*_z$ with depth and time and (2) the needed assumption that thermal diffusivity is constant with depth and time. The present data base also limits the prediction of soil temperatures from the Fourier series model to the top 0.30 m profile, with larger day-to-day variation at deeper depths.

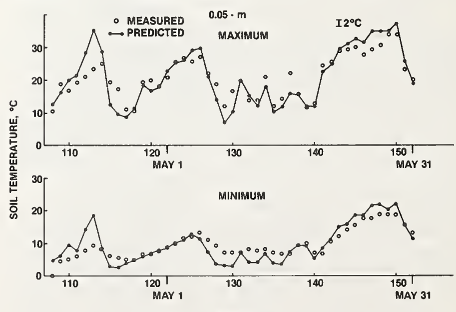

Figure 2.--Predicted and measured daily maximum and minimum temperatures at 0.05-m depth during spring of 1980 at Waseca, MN.

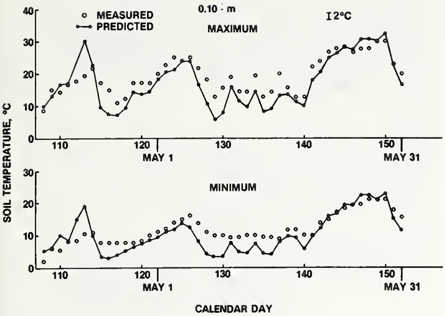

Figure 3.--Predicted and measured daily maximum and minimum temperatures at 0.10-m depth during spring of 1980 at Waseca, MN.

Prediction of Soil Heat Flux

Gupta et al. (1984) calculated hourly soil surface heat flux from equations 10 and 11 for three tillage-residue treatments on 3 May 1982 (figure 4). Thermal diffusivity was assumed constant (0.44 $mm^2\ s^{-1}$) for all tillage (moldboard, chisel and no-till) treatments. Volumetric heat capacity was calculated from the particle size analysis, the bulk density and the volumetric water content data. Volumetric heat capacity varied between 2.14 and 2.55 MJ $m^{-3}{}^{\circ}C^{-1}$. Comparison of curves in figure 4 show that hourly soil surface heat flux is approximately the same for two tillage treatments with similar residue cover (MPSR and NTSR). However, hourly soil surface heat flux is higher for bare soil (NTNR) as compared to residue covered soil (NTSR) for the same tillage condition. Daily soil surface heat flux was 69.8, 47.9 and 42.6 W m^{-2} for NTNR, MPSR, and NTSR treatments, respectively. These observations indicate that during tillage management, change in the surface residue cover is the main reason for higher maximum and lower minimum soil temperatures under moldboard plow as compared to no-till condition. Changes in soil thermal properties due to soil disturbances by tillage result in minimal effects on soil temperatures or soil surface heat flux.

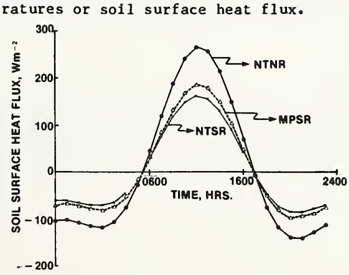

Figure 4.--Hourly soil surface heat flux for three tillage-surface residue combinations on 3 May 1982.

Corn Emergence Model

Figure 5 is the plot of percent emergence of corn planted at 5-cm depth as a function of GDD for various tillage and surface residue conditions. Percent emergence was calculated relative to the total numbers of plants emerged in each treatment on June 9, 1983 (inset table in figure 5). Arrows in figure 5 correspond to GDD when emergence was nearly complete (≈95 percent). On an average, complete emergence corresponds to 60 GDD at field soil matric potential (0 to -10 kPa). The concept of 60 GDD for complete emergence followed the trends obtained in growth chamber experiments which defined the best seed bed conditions for corn emergence (Schneider and Gupta, 1984). In this experiment, the values of 64, 70, 76, and 82 GDD corresponded to conditions when moisture potential was -10, -33, -100 and -500 kPa, respectively, and aggregate size distribution was between geometric mean diameter of 1.0 and 6.8 mm.

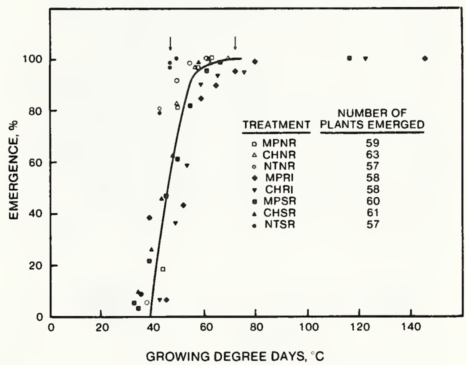

Figure 5.--Relationship between emergence and growing degree days at 5-cm depth under various tillage and surface residue conditions.

Planting Date Model

Soil temperature and corn emergence models were used to develop nomographs of corn emergence vs. planting date for the northern Corn Belt States. The procedure involves the use of daily maximum and minimum air temperature to predict soil temperature at the 5-cm depth from the Fourier series soil temperature model and then accumulating the GDD starting from the day of planting. When the GDD total a value of 60, this would correspond to complete emergence at field soil matric potential.

This procedure was used to derive probabilities of corn emergence at various planting dates. Runs were made for two tillage and surface residue conditions at 11 locations in Minnesota, Iowa, Wisconsin, and South Dakota. Climatic records of the daily maximum and minimum air temperature between April 1 and July 1 for the last 10 to 15 years were used for these runs.

Figures 6 and 7 give the probability of complete corn emergence at various planting dates for MPNR and NTSR treatments. Figure 6 shows that if corn is planted on April 8 under MPNR condition at Waseca, MN, the probabilities are 10, 33, 66, and 100 percent that corn plants would emerge in 3, 4, 5, and 6 weeks, respectively. Weeks mean a range of days. For example, 3 weeks means 15-21 days, and 4 weeks means 22-28 days, and so on. Figure 7 shows that corn emergence is delayed by approximately one week under NTSR conditions as compared to MPNR (figure 6). In figures 6 and 7 are also plotted the frost (<-2.2°C) probabilities and amount of precipitation at the 50 percent probability level. These are constraints that could be used to decide on planting dates. For example, if planting is done on April 1, then in 6 of 10 years the plants would emerge within 6 weeks, that is the week of May 5 through 13. At this time, the probability of frost varies between 10-25 percent. If a farmer can not take a risk of frost setting back or possibly killing the seedling, then he can delay planting by a week (8 April) and lower the frost probability to nearly zero at the time of corn emergence. Figure 7 also shows that delaying the planting by 2 weeks (April 15) delays the emergence by only 1 week (May 13 - 20). Amount of precipitation at 50 percent probability shows that the best time to plant corn would be between May 6 through May 20. This is the period when precipitation is relatively small and soil has had enough time to dry to field-capacity water content either through drainage or evaporation. At Waseca, MN, corn is generally planted between May 1 through May 20.

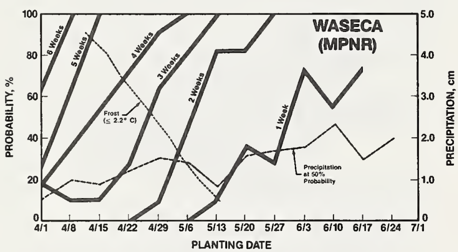

Figure 6.--Probability of corn emergence for various planting dates under moldboard plow with no surface residues (0% cover) at Waseca, MN.

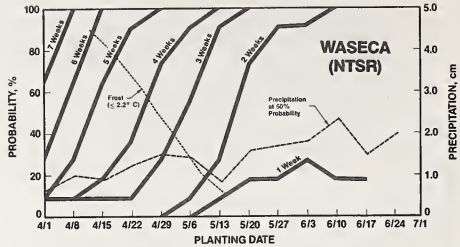

Figure 7.--Probability of corn emergence for various planting dates under no-till surface residue conditions (75% cover) at Waseca, MN.

Similar analysis of probability of corn emergence at 95 to 96° longitude showed that in early spring (8 April) there is a difference of 4 weeks in emergence between 40.7° (Shenandoah, IA) and 45.6° (Morris, MN) latitude North, whereas later in the planting season (27 May),the differences are only 1 to 2 weeks. These observations agree with the intuitive notion that corn emergence in the northern section of the Corn Belt should be late because of cooler soil temperatures in early spring.

SUMMARY

Models are presented that consider the effects of tillage and surface residues on upper boundary and root zone soil temperatures. These models are based on the finite difference and Fourier series solution of the heat flow equation. Input needed for these models are the daily maximum and minimum air temperatures and thermal diffusivity of the soil. Based on the results from a field experiment we also defined number of soil heat units (GDD = 60) needed for corn plants to emerge. Using the concept of 60 GDD with predictions of soil temperatures from daily maximum and minimum air temperatures over 12 years, we developed nomographs on probability of corn emergence at various planting dates for Waseca, Mn. An example of the effect of no-till and moldboard plow practices on probability of corn emergence is discussed.

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A RANGELAND PLANT PRODUCTION MODEL

J. D. Hanson[1], J. W. Skiles[2], and W. J. Parton[3]

INTRODUCTION

Many simulation and mathematical models describing plant growth and development have been produced in the past decade. These models range in complexity from simple regression models (West and Lauenroth 1982) to extremely complex, process oriented models (Innis 1978). Two rather complex plant growth models (Reynolds et al. 1980, Jones et al. 1980) present similar philosophies; they are driven by photosynthesis and subsequently partition-assimilated carbon. Hesketh and Jones (1980) stated the importance of basing crop growth and yield models on photosynthesis to study effects of various policies on agricultural production, the economy and the environment.

The SPUR (Simulation of Production and Utilization of Rangelands) plant growth model is physiologically based and links rangeland plant growth with various environmental variables. The specific objectives for this modeling effort were (1) to develop a model that predicts daily biomass and nitrogen content of green and dead vegetation on rangeland, (2) to simplify the model structure so that the model can handle spatial heterogeneity of range communities by estimating multiple points along several catenae, (3) to minimize data input necessary to operate the model so that it can be used on several types of western rangeland, and (4) to develop the model so that it can aid in making practical management decisions based on the response of vegetation to herbivory and nitrogen availability.

Our model is different in several ways from the other plant growth models (crop models) presented during this symposium. First, this model is not centered around the calculation of photosynthetically active radiation. Second, leaf area index is calculated at each time step as a function of plant growth. Thus, leaf area index is not a graphical function input by the user to drive the production model. Third, the model handles multispecies situations, such as rangeland, but can be used on monocultures with or without weeds or other competitive plants. Fourth, the model allows plants to compete for nitrogen and water resources. Finally, the model simultaneously simulates the production of plants on several sites; thus it accounts for the heterogeneity of the ecosystem.

General Model Description

The USDA-ARS began work in 1981 on a management level simulation model for aiding decisionmaking processes on western rangelands. To accomplish the objectives of the SPUR effort, a mechanistic model of the primary producer component of the grassland ecosystem was deemed essential. A computer simulation approach was undertaken to meet this requirement under the constraint that the computer code be as simple as possible yet realistic and accurate enough to meet the overall model objectives. The model was constructed to simulate carbon and nitrogen flows through green shoots, seeds, live roots and crowns, litter, dead roots, and soil components of rangeland ecosystems. The model was also designed to allow for grazing by herbivores and for man to influence the system by fertilizing and seeding.

Extant models were reviewed during the construction of the primary producer model. The ELM model, developed by the International Biome Project, U.S. Grassland Biome Study, and grassland models developed by Parton et al. (1978), Detling et al. (1978), and Detling et al. (1979) were studied extensively.

Amount of phytomass (total plant biomass) on each day is required output from the primary producer component for the SPUR model. Assimilated carbon is converted to phytomass by multiplying carbon by 2.5. The producer model simulates the flow of carbon and nitrogen through the soil-plant-animal interface. There are seven carbon and eight nitrogen state variables in the model (fig. 1). In the flow diagram, seven of the compartments are divided into two separate components to emphasize the concomitant existence of carbon and nitrogen within the state variables. Species-dependent state variables in the carbon and nitrogen submodels are green shoots, live roots, propagules and standing dead. Dead roots, litter, soil inorganic nitrogen and soil organic matter do not have species identity. If nitrogen and carbon flow in unison between two state variables, the arrow points to the box title. However, if either carbon or nitrogen flow independently, the arrow points to the carbon or nitrogen subcompartment, respectively. Finally, the model in its present form is dimensioned to simulate up to seven species or species groups existing on up to nine range sites.

Abiotic variables used to drive the plant growth processes include daily minimum and

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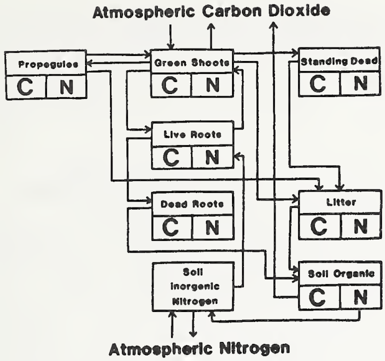

Fig. 1.--Flow of carbon (C) and nitrogen (N) in primary producer model.

maximum air and soil temperature, precipitation, soil water potential (for the wettest soil layer and the (0 to 15 cm depth), total daily solar radiation, and daily accumulated wind run. Soil bulk density is also required by the model.

The ability of this model to simulate rangeland production has been investigated in single and multiple species runs of the model (Skiles et al. 1982). The model produced phytomass and nitrogen simulations typical of blue grama phytomass dynamics in northeastern Colorado. Other runs mimicked the expected dynamics of blue grama and western wheatgrass production and nitrogen flow. The model showed greatest sensitivity to processes controlled by temperature.

Assumptions

In the development of the primary producer model, we assumed that the same functional expressions could simulate C-3 and C-4 plants. Crassulacean Acid Metabolism plants were not included within the constructs of the model. We also assumed that plant competition for water and nitrogen was functionally related to the plant efficiency of acquiring these nutrients. Competition for light and space was not included in the model. To simulate the response of shrubs on rangeland, we assumed that the woody stem material was standing dead. In later versions of the model we will need to include a separate state variable for woody plants. For our purposes, however, we did not find this assumption overly limiting. Other assumptions will be stated as they arise in the discussion of individual processes of the model.

CARBON FLOWS

Growth Initiation

To begin growth in the spring, some leaf area must exist. Leaf area is determined as a proportion of aboveground, green phytomass and is subsequently used in calculations of photosynthesis and respiration rates. The phytomass needed to initiate this process can come from two different sources. When 10-day ambient mean temperatures and 5-day mean soil water potentials exceed critical levels, phytomass is translocated from the roots of perennials to shoots. Roots can support only a limited amount of aboveground green phytomass; therefore, upward translocation stops when a critical root:shoot ratio is reached. Propagules germinate when the 10-day mean ambient temperature and the soil water potential at 0 to 15 cm are at proper levels. In many of the western grasslands this source is less important for perennials than for annuals. The phytomass of germinating seeds is partitioned according to the critical root:shoot ratio.

Carbon Assimilation

Once upward translocation or seed germination establish some aboveground material, the plants can begin to assimilate carbon. In the model, C-3 and C-4 plants function at different rates, depending upon the environmental conditions. Photosynthesis is calculated by first determining the expected maximum rate of photosynthesis as a function of percent shoot nitrogen, temperature, and soil water potential. The expected photosynthetic rate is then reduced according to the present radiation level. Within the model, points along the diurnal cycles of net photosynthesis for each species are computed 8 times each day and integrated to give a total daily amount of carbon dioxide fixed. This carbon dioxide is subsequently converted to phytomass equivalents by multiplying it by the leaf area and the conversion constant.

Translocation

Phytomass can be translocated from the shoots to either the roots or propagules. Translocation from the shoots to the roots must maintain the root:shoot ratio. Thus, if the shoot phytomass becomes too great for the roots to maintain, a portion of the shoot phytomass is shunted to the roots. Also, when senescence begins, large proportion of the new photosynthate is sent belowground. Translocation from the shoots to the propagules is proportional to the net photosynthesis rate.

Mortality and Respiration

Shoot mortality can occur through several mechanisms in the model. First, shoots may

die because of a lack of water. The soil water potential of the top 15 cm is used to estimate the rate of drought mortality. Only a proportion of the aboveground green, however, can die on any one day. Second, chilling can kill green material. In the case of low temperatures a set proportion of the aboveground plant is added to mortality rate caused by drought. Finally, the mortality rate is increased by 1 percent of the aboveground phytomass after senescence begins.

Shoot respiration is calculated as a function of ambient temperature and soil water potential of the wettest soil layer. It is calculated only at night because daytime respiration is included in the calculation of net assimilation rate. The maximum respiration rate is input for each species.

Root mortality is a function of root phytomass, soil temperature, and soil water potential at 15 cm. Under severe conditions all susceptible roots will die. Root respiration is calculated as a function of root phytomass and temperature.

Seeds lying on the ground can also die. The death rate of seeds is simply calculated as a proportion of the propagule phytomass. For simplicity, seeds are not considered to be affected by temperature or water stress conditions.

Effect of Grazing

Herbivores affect the amount of standing green and dead vegetation by consuming the vegetation or by trampling it. Herbivory by consumers is handled by the animal component of SPUR. Thus, the plant production model is only concerned with the trampling effects of herbivores. All of the standing live and green material is available to be trampled, but standing dead is considered to be less resilient than green. Therefore, large herbivores tend to trample standing dead at higher rates than green material. Green and dead material is trampled in proportion to the total stocking rate of domestic and wild herbivores. Also, it is assumed that herbivory does not explicitly act as a stimulant for plant growth. If the herbivores reduce plant cover substantially, translocation from roots and shoots can again be initiated.

Decomposition

Decomposition of dead roots, litter, and soil organic matter are all calculated in a similar fashion. Maximum decomposition rate is determined as a proportion of the respective pool, and the cumulative effects of temperature and soil water potential at 15 cm are used to reduce the rate. Dead roots, litter, and organic matter do not decompose without soil inorganic nitrogen. Also, it is assumed that as dead roots and litter decompose, 40 percent of the carbon is retained and the remaining carbon is lost to the atmosphere.

NITROGEN FLOWS

Nitrogen Uptake by Roots

Standard saturation kinetics are used to estimate rate of nitrogen uptake. Thus, the maximum nitrogen uptake rate and the efficiency coefficient control the degree of competition between species. Once the uptake rate is determined, it is reduced by the cumulative effects of soil temperature and water potential (15 cm). If the percent nitrogen in the roots ever exceeds 1, then nitrogen uptake is not allowed. Also, if there is not enough inorganic nitrogen in the soil to satisfy the requirements of all the species, the nitrogen that is present is partitioned in proportion to the demand of each species. (See the PHOENIX model by McGill et al. 1982.)

Nitrogen Transfer from Roots to Shoots

The calculation of nitrogen transfer from roots to shoots is probably the most critical one in the entire plant growth model. The rate of flow into the shoot directly influences photosynthesis, thereby controlling plant growth. Also, this flow controls the C:N ratio for the aboveground plant and thus affects forage quality and diets and gains of grazing herbivores. The approach taken in this model was very similar to the one used in the ELM model (Reuss and Innis 1977). A graph of the ratio of live shoot to root nitrogen concentrations versus time of year was produced. From the start of the growing season until senescence begins, this ratio is set to 3. The ratio then decreases linearly from 3 until it reaches 1 at the end of senescence. The ratio can never go below 1. If regrowth occurs after the end of the senescence period, the ratio is set to 3 for the remainder of the year. The Julian dates used for the beginning and ending of senescence are user inputs. Subsequently, the positive or negative transfer of nitrogen from roots to shoots is determined to be that amount which preserves this ratio.

Other Nitrogen Flows

In general, when carbon flows from one pool to another, nitrogen is sent at a rate equivalent to the C:N ratio of the donor pool. For example, when cattle trample standing, live phytomass, the phytomass going to the litter pool has the same C:N ratio as the standing, live phytomass. There are, however, several exceptions to this rule. First, when shoots die through natural mortality, the plant "attempts" to conserve nitrogen. Thus, the rate of nitrogen transfer is calculated by adding 10 to the current C:N ratio. Another

case where the nitrogen is not sent at the same C:N ratio occurs in the propagule dynamics. For seed production, mortality and germination the C:N ratio is held constant at 10. Finally, we leach an additional 1 percent of the nitrogen from the material that is being transferred from standing dead to litter.

Belowground Nitrogen Dynamics

Decomposition of dead roots and litter causes a transfer of nitrogen to the organic pool at the C:N ratio of the respective donor. Dinitrogen is converted to soil inorganic nitrogen at rates proportional to precipitation. Nitrogen is mineralized from soil organic material at a C:N ratio of 10. Denitrification occurs at rates dependent upon the 15-cm soil water potential and the concentration of soil inorganic nitrogen. Organic material is maintained at a C:N ratio of 10. The amount of inorganic nitrogen immobilized by the decomposition of litter and dead roots is calculated as the difference between the nitrogen that is needed to maintain the C:N ratio of 10 in the organic matter and the nitrogen that is released by the decomposition of the litter or dead roots.

SAMPLE SIMULATION

Suppose we are interested in knowing the effect of a changing climate on the production of rangeland. Specifically, we are interested in determining the effects of temperature and radiation reductions on aboveground and belowground net primary production, and aboveground peak standing crop. An experiment to test the effect of these climatic changes was conducted on the SPUR model. The factorial experiment was designed using model parameters derived from 1974 and 1975 data taken at the Central Plains Experimental Range (CPER) in northeastern Colorado. The model was run using warm season grasses (WSG), cool season grasses (CSG), warm season forbs (WSF), cool season forbs (CSF), and shrubs (SHR). Treatments were combinations of 0, 3, 6, and 9°C decreases in temperature and 0, 25, 50, and 75 percent decreases in solar radiation (table 1). Means were statistically compared using Tukey's hst. As expected, these types of reductions tended to favor C-3 over C-4 plants and forbs over grasses. Also, reductions in light were more tolerable for all plant groups than reductions in temperature. Under the most severe treatment, 9°C reduction in temperature and 75 percent reduction in light, shrubs were affected the least.

PHASE 2 OBJECTIVES

At the end of phase 1, we have 36 species dependent parameters in the plant growth model. Many of these parameters are hard to determine in the field, and in some cases the literature is void of any information regarding them. Thus, the primary concern for SPUR phase 2 will be to (1) develop a parameter set for each of the target sites outlined by the SPUR modeling committee and (2) work on a method by which the unknown plant parameters can be estimated from a minimal amount of information about each species. Concomitantly, an algorithm to simulate root distribution by species will be added to the model in phase 2. Also, the ability of the model to handle shrubs and annual grasses will be improved. Finally, the code will be reviewed and coding inefficiencies and conceptual weaknesses will be corrected.

SUMMARY

A primary producer model has been developed which simulates aboveground and belowground plant dynamics. It is unique among crop models in that the model is capable of handling multiple species on multiple sites, and it includes a method of allowing the plants to compete for available nitrogen and water. Though the model was originally developed for rangelands, it does work on monocultures. The plant model uses some techniques of previous primary producer models but is unique in its overall complexity and small size (less than 40 K-bytes of storage). Net carbon assimilation is the entry point of carbon dioxide into the plant. Subsequently, carbon and nitrogen contents of standing green, live roots, propagules, standing dead, litter, dead roots and soil organic matter are simulated. Soil inorganic nitrogen is also included in the model. The model produces generally good phytomass and nitrogen simulations and produces results which are typical of shortgrass prairie phytomass dynamics in northeastern Colorado. The model can handle up to seven plant species or species groups on a total of nine range sites. It incorporates processes which are common to C-3 and C-4 plants but does not consider plants with Crassulacean Acid Metabolism. While 36 parameters are required per plant species, many of these are common to most plants and do not need to be precisely input. The model needs to be validated against real data on a variety of range types, including desert ranges, annual grassland ranges and tallgrass prairie. When coupled with SPUR, the plant model will allow testing of grazing regimes, precipitation variation, fertilizer application and seed consumption. The model has been successfully used to simulate a two-species system and shows promise when expanded to entire plant communities. For research and management applications, the model can produce output which will aid in gleaning information at costs significantly lower than direct experimentation. The primary production model should be able to aid managers in making decisions, such as the effect of grazing on range forage production and range condition.

Table 1.--Results from sample simulation of shortgrass prairie showing the effects of temperature and radiation reductions on vegetation dynamics[1]

Factor	Net primary production[2] Belowground	Net primary production[2] Aboveground	Peak standing crop
		Species	
WSG	0.47 c	0.50 c	0.57 d
CSG	0.63 b	0.66 b	0.67 c
WSF	0.65 b	0.63 b	0.65 c
CSF	0.78 a	0.78 a	0.78 b
SHR	0.81 a	0.82 a	0.87 a
		Temperature reduction (C)	
0	0.87 a	0.87 a	0.86 a
3	0.77 b	0.77 b	0.79 b
6	0.59 c	0.61 c	0.65 c
9	0.45 d	0.47 d	0.53 d
		Light reduction (%)	
0	0.77 a	0.79 a	0.82 a
25	0.71 b	0.72 b	0.76 b
50	0.64 c	0.65 c	0.67 c
75	0.55 d	0.56 d	0.57 d

[1]Values represent means for the ratio between treatment and no treatment simulated phytomass.

[2]Means within columns of each factor followed by the same letter do not differ significantly at the 0.05 level. Interaction means were not tested.

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APPROACHES IN THE SIMULATION OF CROP ECOSYSTEM PROCESSES

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INTRODUCTION

In an earlier chapter of this volume, Baker compared and contrasted the strategies used in building models and he pointed out the advantages of process level dynamic models. Here we outline important and sometimes unique features of our approach to the simulation of the major plant processes. We have developed process-level models of wheat, cotton and soybean (Baker et al.,1981, Baker et al. 1983, Acock et al. 1983). These row crops are grown for their fruit, under widely varying ecological conditions. Our remarks pertain, particularly, to crops of this type.

The breadth of the ecological range of these crops dictated a process level approach. Our view that developmental work would proceed into the indefinite future, with updates being provided to the user as new scientific information became available, indicated that the processes should be treated in discrete subroutines.

CROP CANOPY LIGHT CAPTURE

The earliest efforts at Growth Analysis (Briggs et al. 1920) recognized two determinants of yield: light interception, which was treated as a function of plant leaf area, and the net rate of assimilation of dry matter (NAR) by those leaves. When this single plant model was taken to the field and applied to crops, leaf area index (LAI) was substituted for leaf area as the variable determining light interception. Although the model has been widely used, its inadequacies soon became apparent.

Watson (1952) itemized the weaknesses of the Growth Analysis model as including the following:

(1) Green photosynthesizing tissues exist in the canopy besides leaf lamina;

(2) increasing LAI may increase canopy light interception, but it usually reduces NAR because of mutual shading;

(3) leaf senescence reduces NAR in a way which is not easily distinguishable from the reduction caused by mutual shading; and

(4) respiratory losses are associated with the mass of living tissue, not simply with photosynthate production.

An alternative approach, which overcomes some of these weaknesses, is to view light interception as a function of canopy area rather than of leaf area index. In effect, a canopy net assimilation rate is used in place of a plant net assimilation rate.

Although the Growth Analysis model incorrectly assumes that light interception is proportional to leaf area or leaf area index, it correctly assumes that canopy dry weight gain, that is photosynthesis, is approximately proportional to total canopy light interception. This has been confirmed by direct measurements in intact stands by Baker and Meyer (1966), by Hesketh and Baker (1967), and Shibles and Weber (1966), respectively, for cotton, corn, and soybean.

Thus, in GOSSYM (Baker et al. 1983) and in GLYCIM (Acock et al. 1983) the fraction of incident light intercepted is calculated on the basis of the size of the canopy row elements, that is, plant height and row spacing. In cotton canopies planted solid or in regular skip-row patterns with row widths ranging from 51 to 203 cm, we have found that daily percent light capture can be closely approximated by the formula

$$I = 1.05\ Z/R,$$

where Z is the height of the row elements and R is row spacing, (c.f. Baker et al. 1978), and Kharche, (1983). Leaf area is used in GLYCIM to determine what percentage of the light incident on the row elements is intercepted by leaves within those elements. Similarly, in GOSSYM, leaf area is used during canopy defoliation, when LAI falls below about 3 and the canopy begins to leak light to ground. We do not use LAI in the developing crop because there is no unique relationship between it and canopy light interception. For example, the data presented in figure 1 show that, at solar noon, light interception may range from 50 to 90 percent in a cotton crop with an LAI of 3.

PHOTOSYNTHESIS AND RESPIRATION

Photosynthesis and respiration may be calculated either with daily (for example GOSSYM and WHEAT) or more frequent (for example GLYCIM) time steps. In either case data on canopy gas exchange rates are needed. These data are best obtained in closed systems for example gas-tight, controlled-environment (CE) chambers or chambers installed temporarily in field crop canopies. We use sunlit CE chambers (SPAR units) in which temperature, soil moisture, and atmospheric CO_2 are computer controlled. A SPAR (Soil Plant Atmosphere Research) unit is shown schematically in figure 2 (McKinion and Baker, 1983).

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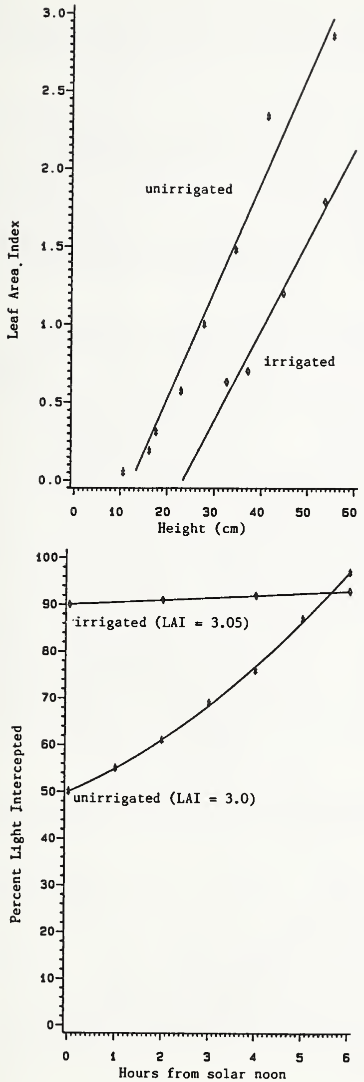

Figure 1. Leaf area index vs. height (a) and light interception vs. sun angle (b) for an unirrigated cotton crop, both with leaf area indices of 3 (Baker and Hesketh, unpublished data).

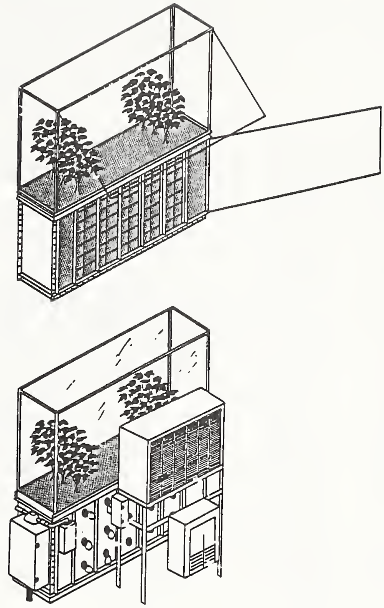

Figure 2. Front and rear views of a Soil Plant Atmosphere Research (SPAR) unit showing plexiglass top and soil bin with glass panels at front and instrument ports at back. The size of the air conditioner is exaggerated in this diagram.

Hesketh et al. (1971) and Baker et al. (1972) have published a data base for the calculation of cotton respiration and photosynthesis under abundant soil moisture conditions. Further experiments by Marani et al. (1984) have extended the data base to include the effects of long and short term droughts on photosynthesis in cotton.

The net photosynthesis (PNET) subroutine from GOSSYM illustrates the major features of our approach to the calculation of photosynthesis and respiration. It is listed in table 1. In lines 1260 to 1263 leaf water potential (PSIL) is calculated from a multiple regression equation in which PSIL is a function of solar radiation flux density (WATTSM) and soil water potential in the rooted portion of the soil profile (AVGPSI). GLYCIM uses a more mechanistic approach to the estimation of leaf water potential, and this is discussed in the section on transpiration, below. In lines 1264 to 1269 a reduction factor for water stress is calculated. The equation for a daily canopy photosynthetic light response curve is solved in line 1275. In line 1276 the day's increment of CO_2 uptake (PSTAND)is adjusted for light interception (INT), water stress (PTSRED) and atmospheric CO_2 levels above 300 vpm and is divided by a plant population factor (POPFAC) to give the amount of CO_2 fixed on a per plant basis. Light respiration (RSUBL) is calculated as a function of temperature (TDAY) in lines 1285 to 1286. Maintenance respiration (BMAIN) is calculated as a function of biomass (PLANTW - COTXX) in line 1287. These respiratory losses are subtracted in line 1288 from the gross CO_2 fixed that day. In line 1290 a growth respiration loss (GSUBR) is removed and the net CO_2 fixed is converted to CH_2O.

Calculation of net carbon fixation in GLYCIM is similar except that several (normally 10) iterations are used during the photoperiod. Photosynthesis rate has a hyperbolic dependence on both CO_2 concentration and on light flux density after adjustment for light interception (Acock et al. 1971). Respiratory losses are associated with the processes of photosynthesis and growth. Light respiration rate is a function of both temperature and CO_2 concentration. Growth respiration is charged at the appropriate rate when it is used to build organs on the plant. Water stress limits net carbon fixation rate through its control of stomatal conductance. Net CO_2 flux may also be limited by low temperature, leaf nitrogen concentration, and leaf senescence (a function of leaf age).

EVAPORATION AND TRANSPIRATION

Of all the models ever proposed to account for water loss from a wet surface, only the Penman equation (1963) attempts to be mechanistic. This equation is therefore employed in all our crop simulators. It is used to calculate potential water loss rates from both crop and soil, with parameters appropriate to each and with allowances made for light interception. However, actual water loss rates are often less than potential rates, and the crop models differ in the way the limitations are handled.

Soil water evaporation in GOSSYM follows the Ritchie (1972) approach of using an empirical relationship between maximum permissible evaporation rate and the number of days since rain or irrigation. In GLYCIM, soil water evaporation rate is limited by the rate at which water can move up to the soil surface. As the surface layer dries, the soil hydraulic conductivity decreases and evaporation is reduced. This mechanistic approach was first used by Rowse (1975).

Actual transpiration rate is derived from potential transpiration rate in GOSSYM by multiplying by a reduction factor. The reduction factor is an (unpublished) empirical function of net radiation, mean daily temperature and mean soil water potential in the root zone. In GLYCIM, it is assumed that the plant takes up sufficient water to meet the potential transpiration demand unless it loses turgor to such an extent that the stomata close. As outlined elsewhere in this volume (Whisler), soil water potential and the amount of root in all parts of the soil profile are simulated dynamically. Knowing the resistances in the water uptake pathways from all parts of the profile, we calculate what the leaf water potential has to be for water uptake rate to equal potential transpiration rate. If this leaf water potential corresponds to a leaf turgor pressure of less than 2 bars, the stomata are assumed to close. Stomatal conductance is decreased linearly from a maximum to a minimum between 2 and 0 bars turgor pressure. Actual transpiration rate is proportional to stomatal conductance over this range of turgor pressures.

The leaf water potential of the upper fully-exposed leaves of the crop is assumed to be the potential at which water uptake rate equals actual transpiration rate.

The approach developed by Parton (unpublished) for determining transpiration in WHEAT is similar to that in GLYCIM; but, in WHEAT, leaf water potential determines stomatal conductance, which determines leaf temperature. Leaf temperature affects the total radiation balance of the leaf, including the amount of latent heat loss that must occur. In a short iterative procedure, a leaf water potential is calculated so that water uptake rate equals the rate at which water must evaporate from the leaf to balance the heat flux equations.

GROWTH

The strategy used in GOSSYM to estimate the growth rate of organs on the plant is as follows:

Table 1. Subroutine PNET

```
      SUBROUTINE PNET
C  ***********************************************************
C  *                                                         *
C  *                  PNET  SUBROUTINE                       *
C  *                                                         *
C  ***********************************************************
      REAL INT,LEAFWT,LYTRES
C
      COMMON /POP   / PN, POPFAC
      COMMON /SOLAR / INT, RI, RN, WATTSM
      COMMON /TEMP  / DTAVG(7), TAVG, TDAY, TMAX, TMIN, TNYT
      COMMON /WEIGHT/ COTXX, GBOLWT, LEAFWT, PLANTW, ROOTWT,SQWT, STEMWT
      COMMON /WETS  / MH2O, POLYNA, PSIAVG, PSIMAX, RAIN
C
      DATA CO2/0./, RSUBO/.0032/, GSUBR/.375/
C PSILIN IS AN INDEX PSI(L) AT 0.3 BARS.
C PSIS AND 27 C. - FULLY TURGID
C PINDEX IS AN INDEX NET P RATE(SAME CONDITIONS).
      AVGPSI = PSIAVG
C PSIL IS MINIMUM LEAF WATER POTENTIAL FOR THE DAY.
      IF(AVGPSI.LT.-2.0) AVGPSI = -2.0
      PSIL = -12.63 + 0.01799*WATTSM - 26.1097*AVGPSI -
     . 0.00001553*WATTSM*WATTSM - 18.289*AVGPSI*AVGPSI +
     . 0.025497*WATTSM*AVGPSI
      PSILIN = -3.82193 - 0.00333224*WATTSM
      PINDEX = -0.101235 + WATTSM*(0.0234135 - WATTSM*0.000017396)
      DPN =  0.24*(PSILIN-PSIL)
      PTSRED = (PINDEX-DPN)/PINDEX
      IF(PTSRED.GT.1.0)PTSRED = 1.0
      IF(PTSRED.LT.0.6)PTSRED = 0.6
C  DATA LEADING TO THIS PTSRED ARE FROM CHAMBER EXPERIMENTS IN INTACT
C  CROP CANOPY (BAKER & HESKETH, UNPUBLISHED 1969).
C  PSTAND, RSUBL, RSUBO, GSUBR FROM BAKER ET. AL. (1972)
C  SIMULATION OF GROWTH AND YIELD IN COTTON: I. GROSS PHOTOSYNTHESIS,
C  RESPIRATION AND GROWTH.  CROP SCI. 12:431-435.
      PSTAND = 2.3908 + WATTSM*(1.37379 - WATTSM*0.00054136)
      PPLANT=PSTAND*INT*POPFAC*PTSRED*0.001*1.06
C  VALUES BASED ON DATA OF HARPER ET. AL. (1973) CARBON DIOXIDE AND
C  THE PHOTOSYNTHESIS OF FIELD CROPS.  A METERED CARBON DIOXIDE
C  RELEASE IN COTTON UNDER FIELD CONDITIONS.  AGRON. JOUR. 65:7-11.
C  AND ON BAKER (1965)  EFFECTS OF CERTAIN ENVIRONMENTAL FACTORS
C  ON NET ASSIMILATION IN COTTON.  CROP SCI. 5:53-56. FIG 5.
      IF(CO2.EQ.1)PPLANT=PPLANT*1.405
C CO2 IS A FERTILIZATION TRIGGER.WHEN CO2 IS EQUAL TO 1,PPLANT IS
C INCREASED 20% DUE TO  500 PPM CO2 CONCENTRATION.
      RSUBL=0.0032125+0.0066875*TDAY
      LYTRES = RSUBL*PPLANT
      BMAIN=(PLANTW-COTXX)*RSUBO
      PTS=PPLANT-LYTRES-BMAIN
      IF(PTS.LE..01)PTS=.01
      PN= (PTS/(1.+GSUBR) * 0.68182)
C  0.68182 CONVERTS CO2 TO CH2O
```

(1) A potential growth rate for each of the organs is calculated as a function of temperature, water stress, organ weight, and time from organ initiation (Baker et al. 1983). At this stage, it is assumed that there is no shortage of metabolites. In the model, no growth occurs in any organ that has a water potential below some threshold (e.g. -7 bar in the case of cotton). Potential growth is calculated for day and night periods separately by using temperature and water stress inputs appropriate to those time periods. A total carbohydrate demand is calculated as the sum of potential growth increments of all the plant organs.

(2) Next, a nitrogen budget subroutine based on the work of Jones et al. (1974) is called. Its function is to estimate the nitrogen required for the assimilation of the amount of carbon just estimated for each of the organs. Priority is given to the growth of fruit. All the nitrogen requirements are summed for the vegetative and for the fruiting parts. The sums are used in the calculation of nitrogen supply/demand ratios. If the ratios are less than one, potential organ growth rates are reduced proportionately.

(3) A carbohydrate supply/demand ratio (CSTRES) is then calculated as follows:

$$\begin{aligned} CPOOL &= PN + RESC \\ CSTRES &= CPOOL/CD \end{aligned}$$

where CPOOL is the total available pool of carbohydrate from today's photosynthesis (PN) plus reserve carbon (RESC) carried in from earlier days, and CD is the carbohydrate demand.

(4) Finally, actual growth of each of the organs on the plant is calculated as the product of potential growth for that organ multiplied by the appropriate CSTRES. In effect, carbon partitioning is controlled by these CSTRES terms.

The data base for these potential growth rates is obtained in SPAR experiments at elevated atmospheric CO_2 concentrations. Temperature and water stress are variables in those experiments.

GLYCIM, being a later model, attempts to be more mechanistic over carbon partitioning. The priorities and controls on carbon use by various organs are shown diagramatically in figure 3. Seeds have the highest priority for all the materials necessary for their growth. This is because annual plants have a strong commitment to seed production, presumably as the result of natural selection during their evolution. Apart from seeds, the other organs on the plant appear to obey the following general principles.

(1) The organs nearest the source of supply of any material have the highest priority on the use of that material.

(2) Partitioning of the materials necessary for growth favors the organs nearest to the source of whichever material is in short supply, that is, whichever is limiting.

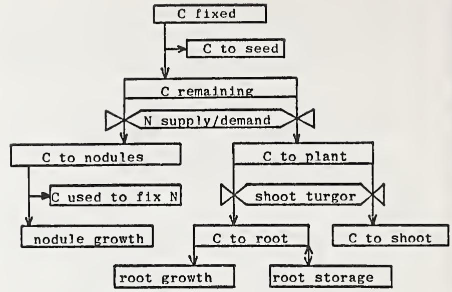

Figure 3. Simplified diagram of carbon partitioning in GLYCIM.

Thus, in GLYCIM, if nitrogen is limiting growth, carbon is partitioned preferentially to the nodules, which can then generate the needed nitrogen. If the plant is under a water stress, carbon is partitioned preferentially to the roots. This is actually done by looking at the changes that occur in leaf water potential during the day. The method for calculating leaf water potential in GLYCIM was described in the section on transpiration, and it was also mentioned earlier that this is normally done 10 times during the photoperiod. From the changes in leaf water potential, changes in leaf turgor pressure are calculated. Green, Erickson and Buggy (1971) have shown that organ expansion rate is proportional to turgor pressure (P) minus a turgor pressure threshold (P'). They have also demonstrated that when P changes, P' changes in the same direction. An empirical model of the rate at which P' changes has been developed from their data, and is found to fit field observations of soybean leaf expansion rates by Wenkert et al. (1978). In GLYCIM, if P changes faster than P' can adjust, leaf expansion is assumed to be inhibited and carbon is diverted from the shoot to the roots. However if P changes more slowly than P' can adjust, the shoot exercises its priority over the carbon supply and the roots do not grow.

The rhizosphere is simulated in all our models as a 1-cm-thick slab of soil which is, typically, the width of the row and 1 m deep. This slab is divided into layers and columns of individual soil cells, typically, each 10 x 10 cm. Cumulative root growth in any cell in the grid must exceed a threshold value before growth can proceed into adjacent cells. From any "parent" cell in the grid, growth proceeds into adjacent cells normalized according to their ability to support root growth. This ability is a function of water content, temperature, bulk density and oxygen concentration. See the chapter by Whisler et al. elsewhere in this volume for a discussion of how these are calculated.

MORPHOGENESIS

The timing of initiation and the abortion of organs in response to stress is handled in a separate subroutine to provide an inventory of parts in the plant. Stress is defined, mathematically, as any factor reducing organ growth. Shortages of water, nutrients and sunlight fit this definition of stress. In GOSSYM, the ratio of actual to potential growth for an organ determines its ability to remain on the plant during a particular physiological age window of vulnerability. Stress also is used as an index of developmental delays. An outline of this subroutine from GOSSYM is presented in figure 4.

Prior to the initiation of the first flower bud (square), the plant is initiating nodes and leaves on the mainstem. Each day after that, it inventories the entire plant, node by node, deciding whether or not to add a new vegetative branch, new fruiting branches, or new nodes on existing fruiting branches. The procedure for this is illustrated in the following steps for the addition of a new node to a fruiting branch.

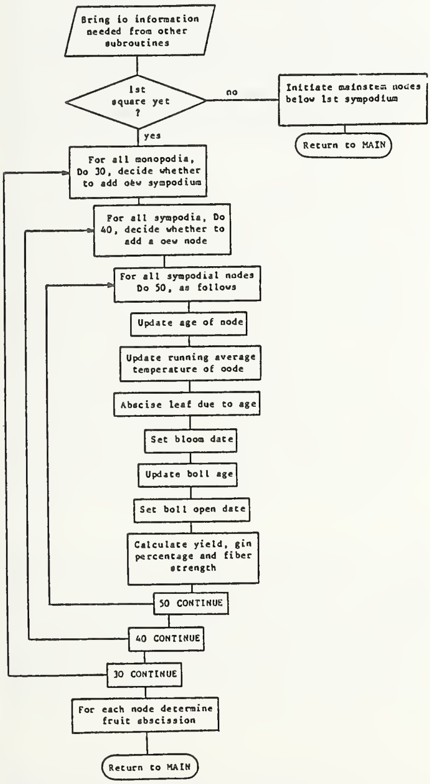

Figure 4. Simplified flow chart of functions performed in PLTMAP.

(1) A delay induced by physiological stress, is calculated from the equation

CDLAYF = 0.89 + FSTRES*(0.2 -2.0*FSTRES),

where FSTRES is the product of the nitrogen and carbohydrate supply/demand ratios. This function was derived from data of Bruce and Romkens (1965) showing development rates in field grown cotton.

(2) These delays are accumulated as follows:

DELAY(K,L) = DELAY(K,L) + CDLAYF + NDLAY

(3) The time interval between nodes under unstressed conditions is calculated as a function of running average temperature since the last node:

TI = (25.1 + AT*(0.81549 - AT*0.056055))*0.51

(4) Whether or not sufficient time has elapsed since initiation of the last node is determined. If it has, a new node with a new leaf and a new flower bud is initiated.

Then, each node on the plant is aged 1 day, its running average temperature is updated, a leaf may be abscissed due to age, the boll age is updated, bloom and boll open dates are calculated, and, in the case of open bolls, yield is calculated.

Finally, the entire matrix is searched again, and fruit are aborted in response to stress. The total number of fruit to be aborted is a curvilinear function of FSTRES. Additionally, fruit may be lost due to insect damage and/or damage due to wetting at anthesis.

Similar logic is employed in the WHEAT model to simulate the initiation and abortion of tillers, spikelets, and florets. In other words, plant development is a resultant of two independent processes, organ initiation and organ abortion. Clearly these are distinctly different physiological processes, responding to different environmental and state variable inputs.

Morphogenesis in soybeans is largely determined by day length and temperature, and this is reflected in the logic in GLYCIM. Apparently, water stress must be very severe before it delays plant development, except at flowering, when the plant seems more susceptible. Branch initiation, pod set and seed set are controlled by carbon availability. As with the cotton and wheat models, organ initiation and abortion are dealt with as separate processes.

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DESCRIPTION OF ROOTSIMU MODEL

Morris G. Huck[1]

This paper presents an update on the model reported in "A Model of Root Growth and Water Uptake Accounting for Photosynthesis, Respiration, Transpiration, and Soil Hydraulics," by Morris G. Huck and Daniel Hillel, published as p. 273-333, Vol. II, Advances in Irrigation, edited by D. Hillel, Academic Press, New York, 1983. The model is a materials balance of carbon and water movement through a plant growing in a one-dimensional, layered soil. It was originally written in CSMP (Continuous Systems Modeling Program, a language supplied by IBM which will automatically generate a FORTRAN program for large mainframe computers). FORTRAN and ACSL (Advanced Continuous Simulation Language) versions are also available from the authors. The original version, published late in 1983, was intended only to demonstrate the feasibility of concepts embodied in the logical structure of the model. A revised version, still in development, uses latitude, daily maximum and minimum temperatures, daily total solar insolation, and other standard meteorological parameters to compute driving functions as a continuous function of time. Parameter-estimation from measurement data in the Auburn rhizotron and collaborators at other locations is now in progress.

The carbon-balance portion of the model considers a labile (nonstructural) pool which is fed by photosynthetic carbon-fixation processes and which supplies growth and maintenance respiration functions. There are also a number of non-labile carbon pools (structural carbohydrates consisting of cellulose, proteins, lignins, and other tissues) which represent the active leaves, stems, and root tissues of the plant. These tissues are formed by transfer of carbon from the labile pool, with a percentage going into structural carbon and the remainder consumed in growth respiration. Maintenance respiration is considered a function of living tissue biomass and temperature. As tissues age, they are removed from the living structural carbon pools at a death-rate computed from factors such as shading (from leaf area index), temperature, age, and availability of labile carbohydrates to drive the maintenance respiration processes.

Present versions of the model consider only vegetative structures (roots, stems, and leaves). In the interest of simplicity, flowering and development of reproductive organs are not considered. Growth of new plant tissue is partitioned between root and shoot in a ratio controlled dynamically by a water stress function computed in the water-balance section of the model. If canopy water potential is high, so that leaves retain turgor throughout the day, most of the new tissue growth will be added to stems and leaves. When soil moisture reserves are limiting and canopy water potential drops, an increasing fraction of the available carbohydrate reserves will be used to form new root tissue. New root growth proceeds fastest in those soil regions having an abundant water supply, while old roots die at a rate proportional to their mass in each layer. Thus, with a half-life on the order of 1 to 3 weeks, active roots are generated in wet soil regions, live only long enough to remove available water, and then die to conserve respiratory energy. The respiratory carbon saved by sloughing old roots is used to generate new roots in soil with more favorable growing conditions. Similarly, older leaves are sloughed when they are shaded by new leaves forming higher on the plant.

The water balance portion of the model is basically the same as that published earlier by Hillel et al. (1976): (Soil Science 121:242-255). A one-dimensional soil is considered homogeneous in the X-Y plane, while a variable number of layers in the Z-direction are used in vertical water flux computations by finite-difference methods. Water is supplied to the soil surface by rainfall or irrigation, and it moves into successively deeper layers by Darcian flow. Lower boundary conditions can be set to constant potential, representing a draining profile; or an impervious lower boundary can be used, as described elsewhere. In addition to Darcian flow between soil layers, however, the root system of the plant described in the carbon-balance section of the model represents a direct connection between each soil layer and transpiring leaves.

Water flow through the plant is considered an Ohm's law analog, with the potential gradient between leaves and each soil layer serving as a driver. Resistance is the sum of stomatal and root components. Stomatal resistance is a function of leaf area index, light intensity, and plant water potential (loss of turgor will induce stomatal closure); root resistance in each layer is the sum of tissue resistance and a soil component based upon water content of that soil layer. Root tissue resistance is divided into an axial (longitudinal) component based upon the size of xylem vessels and distance from the soil surface, while the radial component is a function of endodermal and parenchymal tissue in the individual rootlet. It is inversely proportional to the length of root in any given soil layer, which, in turn, is a function of root mass in that layer.

The published version of the model contains a complete description of each equation in the code, with an alphabetically arranged glossary. Examples of simulation runs are included so that the reader can get a "feel" of how the model performs when parameters are adjusted. Additional experimental data are now available, and parameter-fitting against measurement data is continuing.

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MODELING SOIL PHYSICAL PROCESSES IN CERTAIN CROP GROWTH MODELS

Frank D. Whisler, D. N. Baker and V. R. Reddy[1/]

INTRODUCTION

To date our group at Mississippi State University and collaborators have developed models of cotton, GOSSYM (Baker et al. 1983), soybean, GLYCIM (Acock et al. 1983) and wheat, WINTER WHEAT (Baker et al. 1981).

Many of the soil physical processes are written into the models as subroutines so that they can be transferred from one model to another or replaced by a better version. We will discuss here several of these relationships and how they may vary from one model to another. We will also indicate where future research and/or data are needed.

Throughout this discussion it must be remembered that the soil is treated as a two-dimensional grid or cells. A plant grows at each upper corner of the grid with roots growing down and sideways, depending upon the soil properties. Soil horizons take up at least one layer or more per horizon. The physical properties of each horizon, particularly the surface horizon, may change with time.

Soil Hydraulic Properties

The water/content matric potential (pressure head) relationships and water/content diffusivity relationships are taken from Brooks and Corey (1964) and Gardner and Mayhugh (1958), respectively. They are

$$(\theta_i-\theta_r)/(\theta_s-\theta_e) = (\psi_B/\psi_i)^{(\eta-2)/3} \quad \psi_i<\psi_B \quad (1a)$$

$$\theta_i=\theta_s \quad \psi_i\geq\psi_B \quad (1b)$$

and

$$D(\theta_i) = D_o \exp \beta(\theta_i-\theta_o) \quad (2)$$

where θ_i is the volumeteric water content at the matric potential, ψ_i;θ_s is the saturated (including entrapped air for field values) water content; θ_r is the residual water content; ψ_B is the air entry value for desorption relationships; η is a soil characteristic parameter; D_o is the soil water diffusivity at the water content θ_o; and β is another soil characteristic parameter. The methods for estimating the soil characteristic parameters are given in Whisler (1976).

The hydraulic soil properties are used in the capillary flow and water uptake subroutines. In these calculations fluxes between soil cells are calculated using the diffusivity form of Darcy's Law. Infiltration is calculated in the gravity flow subroutine where the total daily rainfall in added layer by layer to the soil to bring each layer to its respective field capacity. If there is any extra rainfall it is considered as runoff and subsoil drainage.

Cultivation and Wheel Traffic

The models assume that the plant has emerged, and the simulations start at that time. In most crop production, therefore, the main tillage practice to be simulated is cultivation. For most crops under natural rainfall conditions it appears from penetrometer readings that the soil settles back from the primary tillage loosening, to near its pretilled conditions by the time of emergence, except for traffic pans which are shattered by primary tillage. Therefore, the effects of primary tillage and deep soil disturbance, which occur after subsoiling, chisel plowing, and so forth, are ignored. The effects of wheel traffic, however, are taken into account.

In the cultivation subroutine, cultivation is limited to the upper 5-cm of soil and no closer than 15-cm to the plants. It increases the total porosity and saturated hydraulic conductivity and decreases the bulk density of the cultivated zone. The opposite is true in the wheel trafficed zone. Rainfall settles the soil back to its precultivated state, depending upon daily rainfall (or irrigation) amount. Within the wheel trafficed zone the soil physical properties remain constant. It is assumed that by the time of emergence, the wheel trafficed zone has been established and that no further changes take place except for cultivation.

Soil Mechanical Impedance

The effects of soil mechanical impedance are calculated in the root impedance and root growth subroutines (Whisler et al. 1977). A relationship between soil penetration resistance and root growth was published by Taylor and Gardner (1963). It is

$$RG = 104.6 - 3.53PR \quad (3)$$

where RG is the percent root growth compared to nonimpeded growth and PR is penetration resistance in dynes cm^{-2}. The relationship was found to hold for cotton over a wide range of soil types. The relationship between penetration

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resistance, soil bulk density, and soil water content published by Campbell et al. (1974) is used in these simulations as a table look-up procedure. If this relationship is known for other soils, then it could be used. These calculations require the input of the bulk density for each soil horizon to be used in the simulation.

Soil Oxygen Content

The soil oxygen subroutine relies mainly on work reported by the Auburn Rhizotron Group (Melhuish et al. 1974) and by Eavis et al. (1971). The oxygen concentration is calculated for the soil profile using apparent diffusion coefficients and root-soil oxygen consumption rates as functions of the calculated soil water content, temperature and root densities (Melhuish et al. 1974). Root elongation rates are then reduced, as indicated by Eavis et al. (1971), when the oxygen concentration falls below 10 percent or 0.10 atm. Thus, cultivation and wheel traffic will affect the soil aeration as well as normal water flow. The mass flow of oxygen into the soil due to water depletion is taken into account.

Soil Temperature

Soil temperature, as it is now calculated in GOSSYM and WINTER WHEAT in the soil temperature subroutine, would not be affected by cultivation or wheel traffic. It is a multiple regression relationship based upon air temperature as determined by McWhorter and Brooks (1965). The regression equation was based upon a full year's data of air temperature and soil temperatures taken at 5-, 10-, 20-, and 40-cm depths. Since this is a regression relationship developed for an undisturbed soil, it does not take into account changes in surface soil roughness and conductivity due to cultivation.

In the GLYCIM model, the soil temperature is calculated by finite differencing of the heat flow equation (Acock et al. 1983). First, the thermal diffusivity of each soil cell is calculated (DeVries 1966) as a function of soil texture, organic matter, and water content. Simultaneous equations for the heat fluxes at the soil surfaces are solved for the heat flux both upward and downward into the soil. This is done by solving the heat balance equations so that the soil surface temperature, which is unknown, can be eliminated. Movement of heat in every direction within the soil profile is simulated and new soil temperatures are calculated for each soil cell. The equations for the flow of heat between adjacent cells employ d'Arcys' law integrated over time and allowing for the fact that as flow occurs the gradient driving the flow decreases.

TEST AND NEEDS

The GOSSYM model has been rather widely tested. (Whisler et al. 1977; Baker 1979; Baker et al. 1979; Whisler et al. 1979a, 1979b; Marani and Baker 1981; Whisler et al. 1982; Ben-Porath et al. 1983; Fye et al. 1983; Landivar et al. 1983a, 1983b). GLYCIM has also been tested to some extent. (Acock et al. 1981, 1982; Del Castillo et al. 1983). At present the latter is receiving regional validation tests in Southeastern Regional Project S-107. WINTER WHEAT is being validated as part of the AgRISTARS project in the northern Great Plains.

To test the response of GOSSYM to erosion, several runs were made, and the results are shown in table 1. There are several scenarios that one might use in such tests. The soil that we used for this test had a traffic pan between 17- and 24-cm. In the 100-cm profile tests, we assumed that 5-or 10-cm of soil eroded from the surface horizon but that the primary tillage operations had not broken up the pan (that is, disc, harrow only). In table 1 the decreases in yields due to erosion would, as expected, be greater in a dry year like 1980 than a wet year like 1982. Since the same amounts of water and fertilizer were applied in all simulations, the indicated responses are due to root growth, water movement and uptake, and nutrient movement and uptake. In the 30-cm profiles, which is like much of the Mississippi-Alabama Blackbelt soils, it was assumed that the primary tillage operation disrupted the previous year's traffic pan but reformed it a the same depth relative to the soil surface. The results indicate a major decrease in yield when one went from the 100- to 30-cm deep profile, and generally continued reductions in yields due to erosion.

Table 1. Simulated cotton yield as affected by soil erosion

	100-cm Profile		30-cm Profile	
	1980 Dry year	Percent change	1980 Dry year	Percent change
Noneroded	2.82	---	1.91	-32
5-cm erosion	2.58	-9	1.36	-52
10-cm erosion	2.29	-19	1.81	-36
	1982 Wet year		1982 Wet year	
Noneroded	3.06	---	2.63	-14
5-cm erosion	3.12	+2	2.06	-33
10-cm erosion	3.01	-2	1.39	-55

In each of the sections discussed earlier, there needs to be additional research and information gathered. For soil hydraulic properties, there are many other water content/matric potential and water content/diffusivity functions proposed in the literature (Hillel 1972). (However, as was shown in these meetings Brakensiek and Rawls have determined the necessary constants for the Brooks and Corey functions for a large number of soils). Since these functions have different shapes, there needs to be a systematic study of fitting selected functions to a wide range of soil textures, where several values of the water content/matric potential functions are known from experiments. The functions should be selected on the bases of physical meaning and of whether they can be mathematically differentiated. Additionally, we would suggest not only that the data bases being generated by the SCS for representative soil series sites include the range of textures, bulk densities, organic matter, hydraulic properties but also that these values be matched so that corresponding data can be retrieved. Also, the water content at saturation and at 0.05-, 0.5-, 5.0-bar pressure as well as 0.1-, 0.33-, and 15-bar pressure should be determined and archived. The data for field saturated water content and hydraulic conductivity (that is, where there is entrapped air as occurs in the field) needs to be known rather precisely since it influences the simulated results severely. In a GOSSYM sensitivity test, Whisler et al (1979b) found that a 10 percent error in the saturated water content could result in a 20 percent change in the predicted yields. Fortunately, the bulk density and diffusivity relationships are not nearly as critical since they are harder to measure. These data are needed immediately because on-farm application of the crop growth models are considered where an SCS farm map is generally available.

If rainfall amounts for half an hour or shorter periods were available from either remote sensing networks or on-farm weather stations, the infiltration could be more realistically calculated. The concepts of soil surface sealing could also be incorporated as a dynamic part of a rainfall event. To date, however, such data are not available.

The cultivation and wheel traffic and mechanical impedance subroutines need to be more widely tested on other soils and crops. Taylor and Gardner (1963) data are needed for other crops. Campbell et al. (1974) data are being collected for other soils in the Southeast by the ARS group at Florence, SC, but such information is needed for all soils where these models are expected to be used.

The soil oxygen content subroutine needs to be field validated and parameters determined for other soils and crops. This is especially true where periodic flooding is expected or high water tables are present during the crop growing season. Also, as erosion removes the more permeable, more structurally stable top soil, the limitations to root growth posed by both soil impedance and soil oxygen will become more significant.

The GLYCIM approach to soil temperature needs to be incorporated into the other crop models. The uniqueness of not having to know or measure the soil surface temperature makes this method expecially attractive. As stated earlier, however, the soil physical properties for specific sites need to be available in computer accessible form. Validation tests need to be made on other soils and crops.

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MODELING SOIL WATER AND EVAPOTRANSPIRATION ON RANGELANDS

K. R. Cooley, J. R. Wight, and D. C. Robertson[1]

INTRODUCTION

The soil profile plays a critical role in the water regime of semiarid rangelands. Most of the incoming precipitation or snowmelt on these rangelands may be returned to the atmosphere as evapotranspiration (ET) after temporary storage in the soil profile. Available soil water seldom exists for more than a few months each year in the lower precipitation areas because plant transpiration and soil evaporation extract it so rapidly.

Efforts to modify vegetation or water yield must be based on an understanding of the day-to-day variations in soil water status, evaporation, and transpiration. Mathematical models provide one means of assessing the many interactive parameters involved. This report summarizes some attempts to model soil water status and ET on semiarid rangelands in southwestern Idaho.

METHODS

Two models with soil water components were selected for simulating soil water status in addition to ET, and a third model was included to simulate ET only. The models selected were the ERHYM (Ekalaka Rangeland Hydrology and Yield Model) developed by Wight and Neff (1983), the SPAW (Soil-Plant-Air-Water Model) developed by Saxton et al. (1974), and for ET only the Hydrology Component of SPUR (Simulation of Production and Utilization of Rangelands) described by Renard et al. (1983).

Using the SPAW and ERHYM models, daily soil water values were simulated for two sites on the Reynolds Creek experimental watershed (Robins et al. 1965) in 1976-81. Evaluation consisted of comparing measured values obtained by the neutron scatter method at approximately 2-week intervals, with simulated values on corresponding days. The Flats and Lower Sheep Creek subwatersheds were used to evaluate the soil water simulations. For details on site characteristics, soil water measurements, and calibration techniques, see Cooley and Robertson (1983).

Evapotranspiration simulations were compared to both lysimeter measurements, and ET was calculated as the sum of the change in soil water content and precipitation, at the Lower Sheep Creek site. We assumed that no runoff occurred when we based ET on changes in soil water and precipitation, which is generally true for this site. Soil water values at the beginning of the year were used to initiate the model simulations of soil water, and conditions at the beginning of the growing season were used for the ET simulations.

RESULTS

Soil Water Simulations

Soil water simulations using SPAW and ERHYM were made on a calendar year basis for the 1976-81 years at the Flats site, and for the 1977-81 years at the Lower Sheep Creek site. The models were calibrated against the 1979 soil water measurements at the Flats site and then used to simulate soil water status at both the Flats and the Lower Sheep Creek sites, with only watershed parameters and site conditions being changed for Lower Sheep Creek. Simulations were made for each year individually using initial soil water values as measured at the end of the previous year. The models were run for the entire year using inputs of observed temperature, precipitation, and either solar radiation or pan evaporation data.

Predicted and measured soil water status for individual layers and the total profile are presented in table 1 for the Lower Sheep Creek site. These results are similar to those obtained at the Flats. In both cases, the largest deviations were found in the upper two layers, where most of the soil water changes took place. The maximum difference between observed and measured soil water values for the entire soil profile was 14 percent by volume, even though individual layers differed more than that. This occurred because of compensating differences between the different layers and the inherent bookkeeping procedures contained in the models. That such good results were produced by both models is encouraging. It indicates that simulated values well represent measured ones. Further analysis of these results indicated that values produced by ERHYM deviate from observed values more than values produced by SPAW, but ERHYM long-term averages are actually closer to observed averages than SPAW long-term averages.

Regression analysis on model-predicted soil water and measured soil water for each day of observation, provided another method of comparison. ERHYM predicted values correlated better (higher R^2 values) with the approximately 26 biweekly observations than did SPAW predicted values in all but 1 year (1980 at the Flats site). This is in contrast to results shown in table 1, where ERHYM predicted values generally differed more from observed values than did the SPAW predicted values. This indicated that the trends between observed and ERHYM calculated changes were similar even though the magnitude of actual values may have been different.

Precipitation falling as snow may have caused the reduced correlations observed for the SPAW model. Trends between observed conditions and SPAW predicted conditions were opposite at times

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because snowfall was handled as rain. This out-of-phase soil water accounting occurred in late fall and winter. It can be observed in the top layer in figure 1, which compares daily model-predicted values of soil water to biweekly measurements of soil water at the Flats for 1978.

Changes in the lower two layers were very minor except during the first half of 1978, when observed soil water increased somewhat. Both models indicated an increase at, or near, this time. The SPAW model best followed the observed trend in magnitude, although it indicated that the increase started before it was observed. This is probably due to storage in the form of snow which delayed the entry of water into the soil. The ERHYM model which contained a snow accounting procedure followed the actual timing of the soil water better but differed considerably in the magnitude of the change. In general. both models followed the observed data quite well--one being a little better one year or in a certain period, the opposite being true for another year or period.

Evapotranspiration Simulations

Evapotranspiration simulations using SPAW, ERHYM, and SPUR were made on a growing season basis for the 1977-79 period at the Lower Sheep Creek site. Growing-season potential evapotranspiration (ETp) calculated by the three models was quite different. The SPAW and SPUR ETp's were considerably higher than the ERHYM ETp, especially at the beginning of the growing season. Each model used a different procedure for calculating ETp (Wight et al. 1983), so differences were not suprising. The ERHYM radiation-temperature based ETp was calculated by an empirical equation which was developed using alfalfa as a reference crop. Alfalfa requires relatively warm weather before it begins growth in the spring, which caused the low ETp values presented. The SPUR model uses radiation and temperature in a combined equation to calculate potential evapotranspiration. The SPAW model uses pan evaporation as a reference for ETp and a coefficient, and it produced values between SPUR and ERHYM.

Model-predicted and lysimeter-measured cumulative ET curves for 1977 are presented in figure 2. As noted in figure 2, the effects of the ETp on model-predicted ET are reflected by higher ET rates early in the year for SPAW and SPUR than for ERHYM. Cumulative ET as measured with the lysimeter was generally between ET predicted by ERHYM and the other two models up to peak standing crop (about July 1), although SPAW predicted ET was also lower than lysimeter values in 1977 (fig. 3)

For a range area adjacent to the lysimeter, ET was calculated from soil water and precipitation measurements by the water balance method. A comparison of model-predicted and water-balance-calculated cumulative ET for 1979 are presented in figure 3. For the 3 years, water-balance-calculated ET values were usually less than SPUR and SPAW predicted values, and greater than ERHYM predicted values. In all cases SPUR predicted values were the highest. As would be expected, the model-predicted and water-balance-measured ET rates tended to come together at the end of the season, indicating that all available soil water had been evapotranspired.

The division of ET into E and T was also investigated, and T as predicted by the SPUR model was also found to be higher than that predicted by the other two models. Since there were no separate measurements of either T or E, it is impossible to say which model produced the best results. The methods used within the models for limiting soil water extraction could be altered to better match observed trends if measurements were available (Wight et al. 1983).

SUMMARY AND CONCLUSIONS

Both the SPAW and ERHYM models were easily adapted to simulate soil water status for the rangeland sites. The test results indicated that, overall, ERHYM duplicated observed values slightly better than did SPAW. The lack of a snow accumulation and melt routine in SPAW may be the main source of error. This error is more a function of timing than a difference in total soil water at the end of the year, where results for the two models were very similar.

All three models (SPAW, ERHYM, and SPUR) appeared to be functionally capable of simulating ET from sagebrush-grass rangelands. Major differences in the models' performance were evident at the beginning of the growing season, when SPAW and SPUR tended to overestimate ET and ERHYM tended to underestimate it. Of the three models tested, SPAW and ERHYM appeared best able to simulate ET from the study site without some additional "tuning" or calibration. Compared to SPAW and SPUR, ERHYM was somewhat simpler to operate, and the input data were more readily available.

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Table 1. Soil water (in cm) contained in specific layers and in the total soil profile (0-137 cm) at the end of each year (1977-81) at Lower Sheep

Layer (cm)	1977			1978			1979			1980			1981		
	ERHYM	Measured	SPAW	ERHYM	Measured	SPAW	ERHYM	Measured	SPAW	ERHYM	Measured	SPAW	ERHYM	Measured	SPAW
0-23	8.38	6.78	6.76	7.62	5.97	6.07	7.37	6.30	6.10	8.38	6.17	6.05	8.38	8.23	7.26
23-46	7.62	7.06	6.73	4.32	5.72	6.10	4.57	6.50	5.61	5.84	5.72	5.72	8.38	8.38	6.96
46-81	7.37	8.15	9.25	7.62	8.08	8.94	7.62	7.85	8.59	8.38	7.54	8.61	9.65	9.88	10.52
81-137	13.72	13.64	14.40	14.99	14.76	15.19	13.72	13.41	14.83	14.73	13.28	14.68	13.21	15.49	16.21
Total	37.09	35.63	37.14	34.55	34.53	36.30	33.28	34.06	35.13	37.33	32.71	35.05	39.62	41.98	40.95
Difference	+1.46		+1.51	+0.02		+1.77	-0.78		+1.07	+4.62		+2.34	-2.36		-1.03
% Difference	4.1		4.2	0.1		5.1	2.3		3.1	14.1		7.2	5.6		2.5

(From Cooley and Robertson 1983)

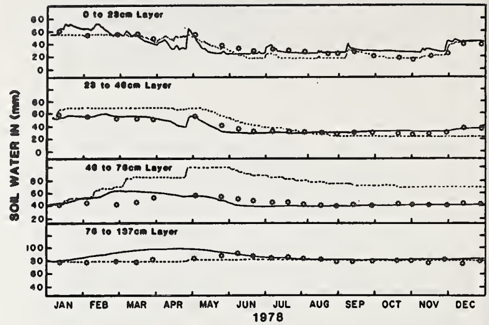

Figure 1.--Field measured (☼) and model-predicted (SPAW = ——; ERHYM = ---) soil water content for four layers, from the surface to 137-cm depth, with time for 1978 at Flats site. (from Cooley and Robertson 1983)

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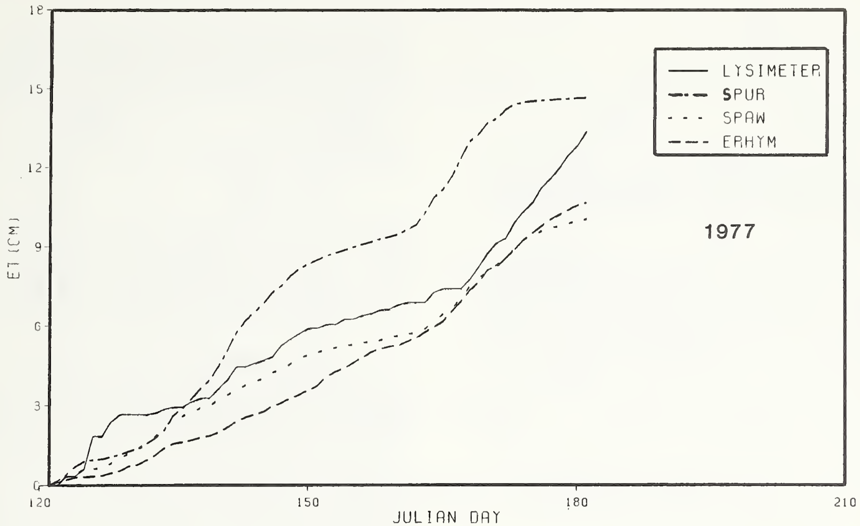

Figure 2.--Model-predicted and lysimeter measured evapotranspiration, Reynolds Creek. (from Wight et al. 1983)

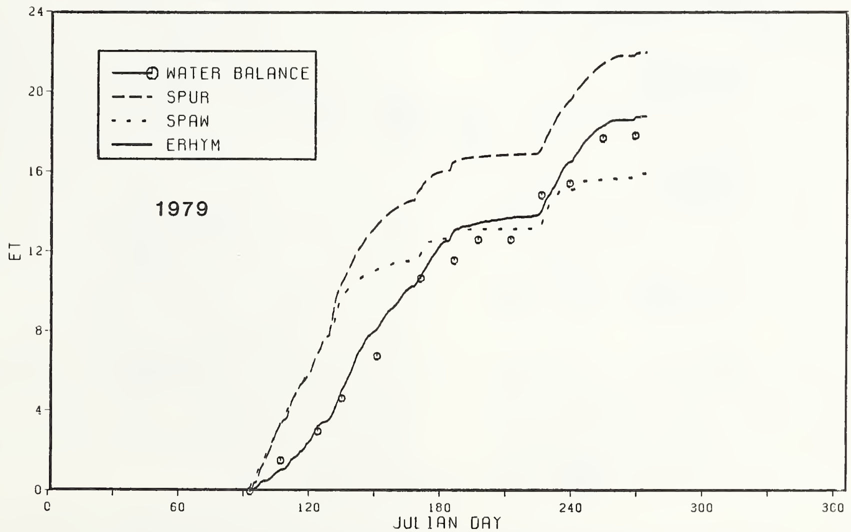

Figure 3.--Seasonal evapotranspiration as determined by the models and water-balance methods, Reynolds Creek. (from Wight et al. 1983)

AN ARIDITY INDEX

Paul R. Nixon[1]

INTRODUCTION

This paper discusses how aridity indexes, as indicators of vegetation stress, can be determined synoptically using thermal data from satellites and air temperatures from weather stations.

The thermal infrared sensing capabilities of current satellites permit the observation of surface temperatures of extensive areas of the earth. The observed temperatures are the result of natural energy exchanges within the landscape (Carlson et al. 1981, Price J. C. 1982).

The energy balance at the earth's surface is expressed as

$$Rn = H + LE + G$$

where Rn = net radiation flux received by the surface
H = sensible heat flux to the air
LE = latent heat flux (evapotranspiration)
G = heat flux to the soil

The latent heat flux (LE) associated with evapotranspiration typically accounts for over 0.8 Rn in well watered conditions. Since the equation expresses the principle of conservation of energy, it is clear that H and G fluxes become increasingly important in partitioning Rn when depleted soil moisture limits LE production.

Soil heat flux, G (the fraction of Rn that enters or leaves the soil), follows flow laws similar to those of water and air in soils. It is usually in the range of zero to 0.3 Rn. However, it is relevant that G is on the wane at the time of postnoon thermal satellite overpasses. Studies have shown that G usually peaks prior to noon and declines during the remainder of the daylight hours, especially under less than adequately watered and less than fully vegetated conditions. Vehrencamp (1953) found that G at a bare, dry soil site decreased from 0.44 Rn at 1000 h to 0.06 Rn by 1400 h on a sunny day.

The sensible heat flux to the air, H, is small under adequately watered and fully vegetated conditions and can, in fact, be negative in environments where heat flows from the air to evaporatively cooled crops (Van Bavel and Fritschen 1964). In contrast, under moisture-deficient conditions, H assumes dominant importance in the transformation of energy. Thus the wide variation in H can be a useful indicator of the degree of aridity, especially as it varies in a given location with changing moisture deficit.

The H can be written as a transport equation (Fedders et al. 1980):

$$H = pc \frac{Ts-Ta}{r}$$

where p is the density of the air; c is specific heat of air at constant pressure; r is the turbulent diffusion resistance (which depends on wind speed, aerodynamic roughness, and atmospheric stability); Ts is surface temperature; and Ta is air temperature.

In a defined geographic region p, c, and r can be relatively constant at a given satellite overpass time for extended periods, or seasonally among years. The change in surface temperature with respect to air temperature (Ts-Ta) is the term that will vary most with the broad changes of H associated with changing LE resulting from soil moisture variations. Thus comparisons of daytime satellite-measured surface temperatures with air temperature are related to sensible heat flux. Said another way, Ts-Ta is inversely related to evapotranspiration.

Prevailing stress conditions can be estimated over large areas by using thermal satellite information to determine the aridity index. This index is defined as the surface temperature of a "footprint" surrounding a weather station minus the air temperature (1.5 m) at the weather station. The daytime overpass of the current polar orbiting meteorological satellite, NOAA-7, occurs at about 1420 h. This roughly matches the time of maximum air temperature for the day. For simplicity the maximum air temperature can be used as Ta when computing the aridity index.

Examples are presented in figure 1 of aridity indexes determined on three dates in south Texas using surface temperatures obtained with the Heat Capacity Mapping Mission satellite. That satellite overpassed at approximately 1410 h and 5.4 km square footprints (9 x 9 pixels) were used surrounding each weather station.

The first date, using data from 13 weather stations, shows clearly the increase of aridity with distance inland from the coast. This was expected because land use changed from irrigated agriculture to rangeland and from an area of coastal showers to a more arid interior. Average annual rainfall decreases about 10 mm/4.5 km with distance inland over most of the area shown.

Comparison of the figures shows the effect of recent rainfall on the middle date (an average of 33 mm at the weather stations during the 5 days preceding 6 June 1978). The aridity index

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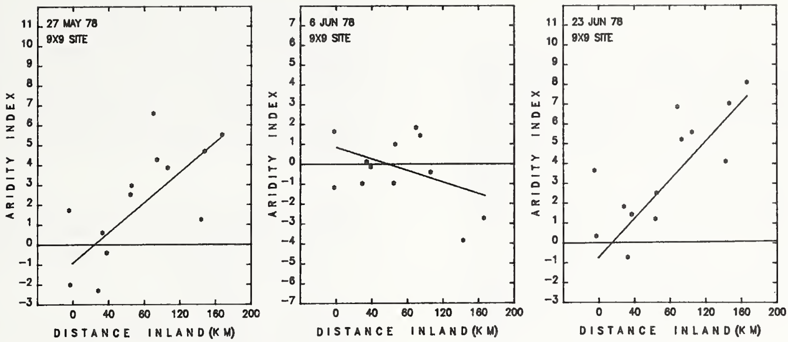

Figure 1.--The aridity indexes of areas surrounding weather stations in South Texas on three dates.

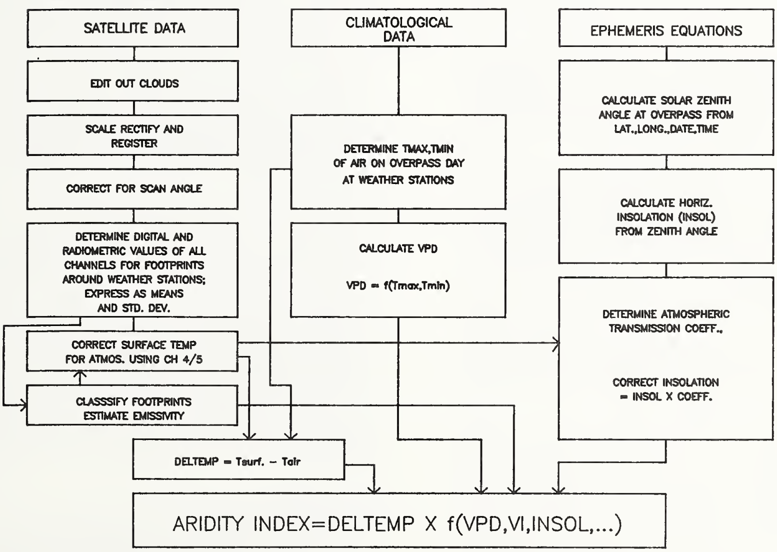

Figure 2.--Steps necessary to determine normalized aridity indexes.

was nil in contrast to the other dates when conditions were dry (no rain for at least 14 days).

REFINING THE SIMPLE (Ts-Ta) ARIDITY INDEX

Defining the aridity index as Ts-Ta oversimplifies the situation. However, the simple definition appears to have worked quite well in the south Texas environment of limited geographic extent. For the method to apply generally and throughout the year, influencing factors such as prevailing vapor pressure deficit, insolation, and varying density of vegetative cover should be taken into consideration. How we are attempting to account for these factors using current NOAA-7 satellite data and other information is shown in figure 2. The necessity of preprocessing satellite data to achieve valid results is also recognized in the chart. Preprocessing includes the removal of cloud contaminated pixels and corrections for scan angle and atmospheric effects.

Figure 2 shows how informtion from three sources (satellite, weather station, and ephemeris equations) might be used to more accurately estimate the aridity index. Work on developing the needed procedures for this is presently underway by the ARS Remote Sensing Research Unit at Weslaco, TX.

SATELLITE DATA

To ensure valid results satellite data need to be preprocessed according to the steps shown in the figure and discussed below. The preprocessing procedures developed in this study will also be useful for improving satellite data for other applications.

Clouds adversely affect satellite data, and individual pixels can be wholly or partially contaminated by clouds resulting in incorrect reflective (VIS) and emissive (IR) values. Cloud contaminated pixels must be removed prior to interpretation if erroneous conclusions are to be avoided about earth surface conditions. Such conclusions include severity of droughts and freezes and their probable economic effects on crop loss. The removal of contaminated pixels is especially important in the analysis of thermal satellite data for applications such as the aridity index.

Besides contamination by visible clouds, there is an additional phenomenon, which is apparent in some satellite scenes: the presence of subvisible atmospheric layers that absorb and reradiate thermal emissions. Visual comparisons of matched VIS and IR scenes of the same overpass show that the clouds have the same pattern and areal extent. However, there are additional patterns in some IR scenes that have no counterparts in the corresponding VIS scenes. The more pronounced patterns seen in the IR scenes can sometimes be observed in the VIS scenes, but the edges are very diffuse and the effects are too subtle to be readily detected in the usual automated processing of digital VIS data. We attribute these patterns, readily discernable in the IR scenes but not apparent in the VIS scenes, to absorbing-emitting atmospheric layers which we loosely refer to as subvisible cirrus. Techniques are being developed for removing visible and subvisible cloud contamination by subjecting satellite data to screening, pixel by pixel, in two-dimensional spectral space (Nixon et al. 1982).

Represented in a step of figure 2 is scale rectification and registration of satellite data to a geobase using established computer techniques. This facilitates analysis by relating satellite data to weather station locations.

Scan angle corrections for changing attenuation must be made because the path length through the atmosphere varies from the satellite to the various pixel locations on the earth. The path length is greatest at the edges of the scene and least at nadir in the middle of the scene.

Determinations by satellite of the surface temperature of the landscape must take into account atmospheric effects on the observations. Using radiosonde data in a radiative transfer model Wiegand et al. (1981) found that corrections ranging from -0.2°C on a cold winter night to +9.8°C on a humid summer day were required in south Texas. The multiple infrared channel method of making temperature corrections may be possible with NOAA-7 and similar satellites. This method, based entirely on data from the satellite, establishes the corrections by comparing the apparent temperatures measured in two or more infrared bands that have different absorption characteristics (Deschamps and Phulpin 1980).

The vegetation (or lack of it that exposes soil) influences the observed surface temperature. Satellite sensors in the visible and near-infrared spectral range can provide information on the amount of vegetation present. Because of its importance, a vegetation index should be used as a normalizing factor in determining the aridity index based on the difference between landscape temperature and air temperature. The vegetation index can also be a guide in estimating the emissivity of the scene. By taking into account the emissivity of the surface it is possible to improve surface temperature estimates.

CLIMATOLOGICAL DATA

Jackson et al. (1981) have shown that the prevailing vapor pressure of the air influences the difference between the surface and air temperatures (DELTEMP of fig. 2) at a given vegetative

stress. Wiegand et al. (1981) found that the vapor pressure deficit was the first (primary) variable selected in a stepwise multiple regression analysis of the temperature data of the Heat Capacity Mapping Mission satellite. Thus the observed DELTEMP must be normalized for prevailing vapor pressure deficit. C. R. Perry, Jr., Statistical Reporting Service, Houston, TX (personal communication) is finding that practical estimates of vapor pressure deficit at NOAA-7 satellite afternoon overpass can be made from daily maximum and minimum air temperatures using a multiplicative model in a range of climates.

EPHEMERIS DATA

Research needs to be done on the influence of prevailing insolation on DELTEMP with respect to vegetation water stress. Ephemeris equations from the literature can be used to calculate insolation for any time, date, and place, excluding the effects of atmospheric transmission loss. This can be applied to specific locations at satellite overpass time. It may be possible to estimate the atmospheric transmission coefficient for correcting insolation to the earth's surface using the satellite derived atmospheric corrections. There might be a relationship between atmospheric transmissivity and the corrections determined for the reflective and emissive satellite data.

SUMMARY AND CONCLUSIONS

We have shown that differences between satellite measured surface temperature and air temperature are related to aridity. An approach is suggested to more accurately measure the aridity index, and thus improve the estimation of vegetative stress conditions.

Some of the procedures needed for refining satellite data, and the aridity indexes derived from them, are available. Others of the procedures discussed have yet to be established or developed. While some of the procedures for processing the satellite and air temperature data may seem complicated, they are of a form that permit automated computer processing. Hence the use of the aridity index promises to be a way of evaluating current stress conditions existing over extensive land areas.

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REMOTE SENSING HYDROLOGIC PARAMETERS USEFUL FOR CROP MODELING

Albert Rango[1]

INTRODUCTION

Remote sensing can be used to measure or calculate several hydrologic parameters which could also be useful in crop modeling. These parameters are stream discharge, snow properties, frozen soil, and soil moisture.

SEASONAL WATER YIELD

The areal extent of snow cover in a basin as determined from remote sensing has been found to be an important parameter for estimating seasonal water yield from snowmelt. The snow-covered area can be used as an additional parameter in traditional statistical approaches for estimating discharge resulting in a reduction in forecast error (Rango 1980). As discussed in other papers at this symposium, the zonal snow-cover extent is a direct input parameter for the deterministic Snowmelt-Runoff Model (SRM) used for making both short- and long-term forecasts of flow (Martinec et al. 1983). Both the statistical and deterministic approaches can be used to generate information on expected water supplies for irrigated regions of the Western United States. The improved knowledge of future water supply quantity and timing is useful in estimation of crop growth and yield in areas dependent on surface water for irrigation.

WINTER CONDITIONS

Information on snow and soil conditions during the winter is useful for estimating winterkill and its effects on yield of crops such as winter wheat. Winterkill estimates require data on snow depth and soil freezing. Fortunately, microwave techniques can supply much information on these two important parameters. Currently, passive microwave radiometer observations at several wavelengths permit measurement of snow extent, snow water equivalent or depth under dry snow conditions, onset of snowmelt, and detection of frozen soil. The advantages of these techniques is that measurements can be made under all weather conditions, over large areas, and on a regular repetitive basis. The disadvantages include poor spatial resolution with current satellites; lack of an adequate means for quantifying the effects of snow grain size, layering, and refreezing; and difficulty in quantifying the information on frozen ground.

Figure 1 is an example of the relation between microwave brightness, T_B, and snow depth taken from a Russian test site where winter wheat is an important crop (Chang et al. 1983). An empirical relation is shown as well as the expected result based on radiative transfer modeling. It can be seen that the relationship covers the range of snow depths important for insulation of winter wheat during midwinter. The empirical relation shown is similar to results obtained over the high plains of the United States and Canada (Rango et al. 1979). Significant additional research is needed to develop the technology to the point where it can be used operationally.

SOIL MOISTURE

Much research has been conducted on remote sensing approaches to measure soil moisture. The two most promising approaches involve the use of microwave and thermal infrared data. Figure 2 is a conceptual scheme for using remote sensing data to obtain soil moisture information. The observations that can be used include microwave brightness temperature (T_B), radar backscatter coefficient (σ_o), surface temperature (T_{surf}), and reflectivity (r). In addition, information on vegetation cover, land use, and soils from conventional or remote sensing data sources is required. The data are used in an algorithm for estimating the surface (0-10 cm) soil moisture. The surface soil moisture is then used, along with meteorological data, to drive a soil moisture model. Point measurements of soil moisture can be used to calibrate or correct the model. The outputs of the soil moisture model are profile soil moisture and evapotranspiration estimates useable in a variety of hydrological and agricultural applications.

A major research effort is underway to develop the relationships between the remote sensing data and soil moisture. Three major elements of the research program currently exist. The first is a truck program designed to study sensor-variable relationships under controlled conditions in confined plots. The second phase of the research involves an aircraft program designed to study soil moisture on a large scale, extend truck results, and investigate potential applications such as hydrologic simulation, irrigation scheduling, and crop yield estimation. The data from the first two phases are used in the third phase, namely, modeling to understand the basic physics. A final phase of the program, not yet underway, would be to extend the soil moisture measurement capability to satellite platforms. Although all phases need additional research, more than enough information is available for specifying a satellite soil moisture observing package. Availability of such satellite data would result in many immediate applications.

CONCLUSIONS

There are several hydrologically related parameters available from remote sensing that could profitably be used in crop modeling. They include seasonal water yield, snow depth, frozen soil status, and surface soil moisture. More specific research is needed for better

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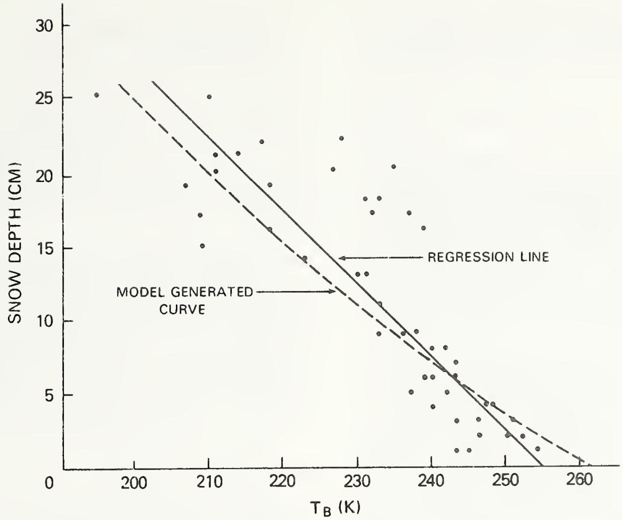

Figure 1.—Nimbus-7 SMMR 37 GHz vertically polarized microwave brightness temperature (T_B) vs. snow depth (Russia).

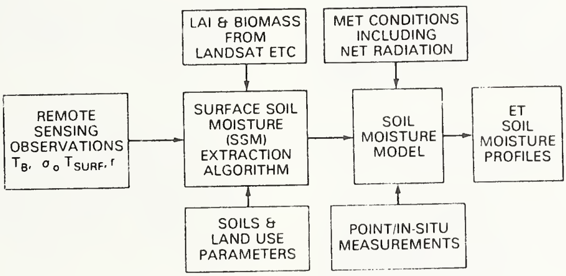

Figure 2.—Conceptual scheme for obtaining soil moisture information from remote sensing data.

fundamental understanding of relationships; however, experiments to test the data in certain applications are ready to be conducted and should be initiated.

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SPECTRAL INPUTS TO AGROMETEOROLOGICAL CROP GROWTH/YIELD MODELS

Craig Wiegand[1]

INTRODUCTION

Plant growth and yield models that integrate plant response to soil and aerial environments, and which simulate photosynthesis, evapotranspiration, dry matter accumulation (growth), phenology, stress response, and yield, typically increment daily and require, as a minimum, the meteorological inputs daily maximum and minimum air temperature, insolation, and precipitation, and the soil inputs depth of rooting and plant available water (fig. 1.).

The purpose of this paper is to stimulate thinking and efforts to use spectral data (0.35 to 14 um wavelength interval), or parameters derived from them to either (a) drive such agrometeorological models, or (b) serve as independent feedback to override and reset or replace simulated canopy development and grain yield (Wiegand et al., 1979; Richardson et al., 1982). The main advantage of the approach is that spectral observations permit a direct look at the crop canopies. Consequently, spectral observations can be responsive to within and among field variations in stresses (nematodes, disease, salty soil, herbicide residues, atmospheric pollutants), past and present management and cultural practices (residual fertility, tillage, crop residue management, growth regulator applications) and soil type that are difficult to include in traditional model inputs.

AGROMETEOROLOGICAL CROP GROWTH/YIELD MODELS

The crop growth/yield models form the core of the interrelationships illustrated in the flow diagram of figure 1. The input variables are obtained from various sources. The process subroutines are developed from data available in the literature and from conducting specific experiments that provide the needed relationships. A subroutine not listed in figure 1, but which is crucial to successful simulation of any crop, is the one for phenology or ontogenetic development of the crop.

We accept the agrometeorological models as they exist for a given crop. Further discussion is on how spectral inputs or surrogate equivalents can be used to: drive the models, periodically check on model simulations and reset or override them, or provide independent assessment of probable yields.

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SPECTRAL INPUTS AS MODEL DRIVERS

Canopy Temperature

Thermal time or heat unit summations based on canopy temperature should relate more closely to crop development than do summations based on daily maximum and minimim air temperature. However, growth models have not been imposed, to my knowledge, in experiments in which canopy temperature has been monitored continuously by infrared thermometry.

The relation between canopy temperature (Tc) and air temperature (Ta) is being elucidated by Jackson and co-workers (1982). The resulting understanding of effects of vapor pressure, net radiation, and aerodynamic resistance on the canopy minus air temperature difference (Tc-Ta), will eventually help quantify both plant response to drought and evapotranspiration rate (Wiegand et al., 1983), and thereby enable the models to more closely simulate reality.

Vegetation Indices

Spectral vegetation indices such as "greenness" (Kauth and Thomas, 1976), the perpendicular vegetation index (PVI) (Richardson and Wiegand, 1977), and the normalized difference (Tucker, 1979) are highly correlated with LAI, green phytomass, and percent cover and consequently with photosynthetically active green phytomass. The growth models typically use LAI in both the photosynthesis and evapotranspiration subroutines.

Direct Estimates of Light Absorption

Since vegetation indices are highly correlated with the photosynthetically active green phytomass, it may be anticipated that vegetation indices might relate directly to light absorption. Hatfield et al. (1984) applied the intercepted photosynthetically active radiation (IPAR) versus LAI equation,

$$IPAR = 93.5\ (1- e^{-0.9\ LAI})$$

to estimate IPAR, then related that estimate of IPAR to the normalized difference (ND) corresponding to Landsat MSS bands 5 (0.6 to 0.7 um) and 7 (0.8 to 1.1 um) expressed by

$$ND = \frac{MSS\ 7 - MSS\ 5}{MSS\ 7 + MSS\ 5}.$$

The relation between IPAR (%) and ND (unitless) was linear with a coefficient of determination, $r^2 = 0.96$. Their and other results indicate that IPAR can be estimated directly from the vegetation index.

Spectral Profiles

Another way to use vegetation indices is illustrated in figure 2 with Landsat data for grain

sorghum fields. The mean PVI for irrigated and dryland fields, for each year are expressed as spectral crop development profiles (Crist and Malila, 1980). The spectral profiles are defined by equations of the form

$$PVI = a\,(t-to)^b\, e^{c(t-to)^n}$$

in which t = day of the year
to = emergence day
a,b, and c = constants with values close to unity, and
n = approximately 5 for sorghum.

The left side of the spectral profiles represent green-up or development of the crop and the right side the brownout or senescence of the crop. The slopes at the inflection points on each side of the curve express the rates of green-up and senescence in the units PVI/day, and the area under such curves between the flex points is an integral crop greenness analogous to leaf area duration. The curve fitting procedure enables one to assign a maximum PVI (PVI_{max}) for a particular field or site and to date its occurrence for each crop season. If the emergence dates for particular fields of interest or spring green-up dates of winter cereals and pastures are unknown the curves help estimate them (Badhwar, 1980). Sorghum reaches PVI_{max} in such curves in extreme south Texas close to day 140 (20 May) (fig. 2).

The curves for irrigated fields in figure 2 are quite similar; however, canopy development observed for the dryland (rainfed) fields was limited by available soil water. In terms of grain yield, 1975 was an extreme drought year, 1977 was a below average year, and yields in 1976 were above average. The rainfall was low in the crucial months March and April of both 1975 (22 mm) and 1977 (13 mm) (Wiegand, et al., 1983), but it is not apparent from the rainfall data that the grain yields would differ as they did. Evidently, the vegetation index sensed crop condition that related to grain yield. The use of spectral vegetation indices to characterize crop canopies is advocated.

SPECTRAL CHECKS ON MODELS

Diverse stresses such as nematodes, saline soils, tight soils, and drought either restrict rooting or reduce the availability of water to the plants so that their common manifestation is a reduction in leaf production and expansion; consequently, canopy size and cumulative phytomass are reduced. Foliar diseases and even poor stands are similarly manifested. The manifestations, but not the causes, should be detectable in the spectral profiles or vegetation indices for the individual fields of interest. If the vegetation indices are considerably higher or lower than those corresponding to the LAI and phytomass simulations of the agrometeorological model, a decision to override and reset the model can be made.

Models predict how crop canopies should be developing, based on model inputs, whereas the spectral data provide information on how they are actually doing.

SPECTRAL ESTIMATES OF YIELD

Spectral data can be used, also, as an independent predictor of grain yield, although many researchers and research managers remain skeptical. However, the capability is consistent with the following generalizations: The better the growing conditions, the healthier and more vigorous the individual plants grow (Wiegand et al., 1974). As a result, canopies intercept light effectively and individual plants have good yield potential. On the other hand, stresses such as drought reduce leaf area and phytomass production. Over the range of seeding rates and management practices used in an area, there is plasticity (through tillering and individual culm weight) in phytomass production, but the harvest index (Donald and Hamblin, 1976) is essentially constant. Consequently, over the range of commercial cultural practices there is a linear relation between the spectral vegetation indices and grain yield.

Figure 3 illustrates the relation between grain sorghum yield (kg/ha) in South Texas and Landsat MSS5 and MSS7 band observations expressed by the perpendicular vegetation index (PVI). The data were obtained during the grain filling stage for the crop seasons 1973, 1975, 1976 and 1977. Some of the fields were irrigated whereas others were rainfed. The symbols T and S on the figure designate irrigated fields in which the sorghum was planted two rows 25 cm apart on beds 1 m apart, and as single rows 1 m apart, respectively. The symbol D designates single rows 1 m apart under rainfed (dryland) culture. The finding is remarkable considering the diversity in weather, soils, grower practices, and genetics represented in the four years of data. It is taken as strong evidence that the vegetation indices capture information about the vegetation canopy responses to soil and aerial environments that relate to grain yield.

Grain yield is expressed (fig. 3) by
Yield (kg/ha) = 840 + 227 (PVI).

For the production area where the relation was developed an average PVI for the irrigated sorghum is 16, corresponding to a yield of 4470 kg/ha, whereas it is 10 for rainfed sorghum (3100 kg/ha). If one has the spectral data to determine PVI in other years (fig. 2) then it is known whether the crop is better or worse than average and the yield deviation from the average can be calculated from the regression equation. Used in this way, the vegetation indices help quantify the effects of stresses on yield.

In summary, the spectral and micrometeorological data used together should provide more accurate

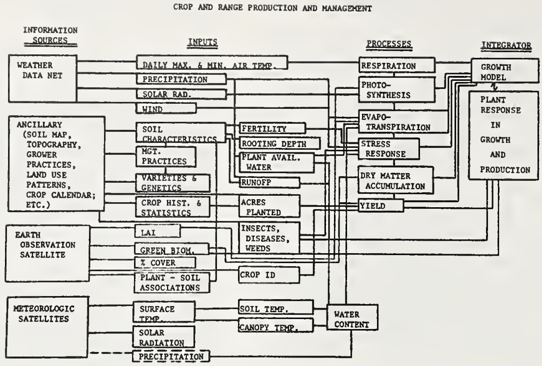

Figure 1.--Information sources, inputs, and plant processes for plant growth and yield models.

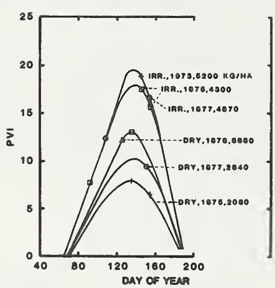

Figure 2.--Seasonal vegetation index patterns (spectral profiles) for irrigated (IRR) and rainfed (DRY) sorghum fields in each of three years. Grain yields in kg/ha are also given.

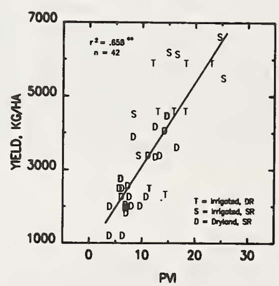

Figure 3.--The relation between the perpendicular vegetation index (PVI) derived from LANDSAT band 5 (0.5 to 0.6 um) and 7 (0.8 to 1.1 um) observations during grain filling and yield of sorghum fields in 1973, 1975, 1976, and 1977.

assessments of crop conditions and yield than either kind of data used alone. Thus, efficient and effective models will be neither purely one nor the other, but hybrids.

ACKNOWLEDGMENT

Appreciation is expressed to A. J. Richardson for implementing the spectral profile equation and derivable parameters on the local computer and to R. D. Jackson for stimulating discussions on spectral inputs to models.

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INTERFACING CROP AND RESOURCE MANAGEMENT MODELS - (PANEL)

M.J. Shaffer, J.K. Radke, and S.C. Gupta[1]

INTRODUCTION

Interfacing of simulation models into comprehensive packages capable of addressing the broad and complex nature of the soil-crop system is one of the most challenging research problems currently being investigated. The necessity of involving interdisciplinary teams and providing proper support and management over relatively long time periods has been demonstrated on numerous occasions. Technology transfer of the resulting product out to users of these models has been cited as a high priority item.

The current status of USDA-ARS soil-crop models was outlined and discussed at the Pingree Park Natural Resources Modeling Symposium. Both strong and weak points of this modeling program and modeling being done elsewhere were addressed in various ways by the participants. Strengths of the present program include--

1. Isolated bits and pieces of information are finally being brought together and put into forms which can be more readily used.
2. Modeling stimulates a higher degree of interdisciplinary exchange than often occurs in other research.
3. A broad base of models is being developed which will (and already does in many cases) provide the basis of resource management studies.
4. Existing models provide the nucleus for the development of future models of all types, including more sophisticated research simulators, engineering models, and models more suitable for direct use by the general public.
5. Existing models have pointed out gaps in our basic knowledge of the soil-crop system and shown where problems exist with our data bases.
6. Existing models have proven to be excellent learning tools both for the model developers and for students (and others) who make use of these tools.
7. Resource managers and politicians are demanding immediate answers to long term problems. In many cases there simply is not enough time to collect data using conventional techniques. Existing and future models are the only other means of addressing many of these issues and problems.
8. Simulation models at the research level often can provide the means to do additional research. This is a case where new knowledge is derived from the application of the model. More information is gained than what was put into the simulator. This area has to be one of the most exciting and promising aspects of model development.

Areas of the program which need improvement include--

1. Administrators of modeling programs often underestimate the time frames necessary to develop and validate simulation models. This is usually caused by a lack of. understanding of what work is being done and the complexity of the problems being addressed. Closer communication between the modelers and the administrators, plus the eventual increased numbers of administrators with modeling background should help to alleviate this problem.
2. Nearly everyone agrees that model validation is an essential part of any modeling program. Yet no one has ever defined what they mean by a validated model. How many data sets must be run through a model and how well must the model results agree with the observations? At the present time, the entire concept is completely qualitative and often steeped in politics.
3. Exchange of model source code and data is an extremely slow and difficult process. Present telephone communication lines are too slow and too unreliable to transmit programs and data over long distances. Computer tapes must be written and sent through the mail. This involves a considerable delay and updated information from a common source is not possible. Consideration should be given to establishing a satellite communication system which can be used to transmit at high speeds over long distances.
4. Both spacial and temporal variability of field measurements which provide input data for models and other purposes have not been adequately addressed from the standpoint of their relationship to modeling. Some progress has been made in this area by the climate modelers and the soil physicists, but considerable additional work is needed to interface field variability into model runs and model output. Variability and uncertainty associated with model coefficients is another aspect of the same overall problem.
5. Field and laboratory researchers are not currently making adequate use of existing simulation models in the design and analysis of their research programs. Much could be gained by simulation of in the problem areas they are studying. The burden of increased awareness of model capabilities lies, in part, with the modelers, but equal responsibility must be placed on these researchers to become familiar with new techniques as they become available.
6. Present data bases are not adequate for modeling purposes. Although a significant amount of information exists in the form of data useful for model development and validation, the material exists in a highly

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disperse form which is difficult and time consuming to access. We need a centralized data management system which is maintained and updated and which is easily accessible to researchers in various parts of the country. Along with the actual data, information should be supplied as to the type of instruments used, the time or integration intervals, the accuracy and reliability of the data, and the spacial and temporal variability of the data source.

7. New methods are required to make better use of existing models and the types of information they generate. Models can be linked together and used to supply information as part of a network. Techniques currently being developed in the artificial intelligence (AI) community for expert systems applications may have some utility in agricultural modeling. The use of these techniques together with existing simulation models and data bases may provide a valuable link between model development and model application and use on a routine basis.

MODEL INTERFACING

Interfacing of models with the user community is one of the most challenging and least understood aspects of the entire modeling process. Ideally, the audience for a model should be specified and their needs determined before a model is developed. Historically, this almost never happens. A research team designs and develops a model which they often perceive as representing the state of the art. The model is then "sold" to whatever user group is willing (and able) to use the tool. One result of this situation (not necessarily bad) is that we have a range of models all of which are advertized as the "ultimate tool" from the viewpoint of the modeling group. Modelers should be willing to discuss both the strengths and weaknesses of their model(s). Administrators need to be aware of the shortcomings as well as the strengths of the products they are supporting.

Considerable effort has been expended in recent years to make both computer hardware and software (models) easier to access and use. At some point each model should have an interactive operating system and be fully accessible from a remote time-sharing terminal or microcomputer. This applies both to research type simulators which reside on mainframe computers and to less complex applications models suitable for minicomputers and microcomputers. The older method of requiring that all model input data be placed in files or on data cards in some rigid format should be avoided whenever possible. The interactive modules for these models should be user friendly in that they display the inputs logically, use default values, give ranges, and specify the units. In addition, the user should not be able to enter values (or other information) which cause the program to abort or compute bad results. A HELP or similar command should be provided which allows the user to list additional information about a particular input item or the entire model, and to exit the program in extreme situations (that is, press the panic button). An internal menu structure should be established which allows input data already entered to be listed and modified without exiting the program.

EXPERT SYSTEMS

One of the best ways to increase the use and applicability of existing models is to make them more problem oriented. Users often complain that, although the models they are trying to use appear to be excellent, they have difficulty applying the tools to solve their particular problems. They say they just don't know enough about the model to make effective use of it. One solution to this dilemma is to hire the model developers to make the applications of interest. This technique has been shown to work but probably is a waste of valuable talent which might be better used in the development of new models.

A better solution to this problem might be to develop problem oriented "front-ends" for groups of models. These would allow users to enter the system at the problem level and tell the computer what they are trying to accomplish. The front-end or expert system would then suggest ways in which the particular problem could be solved and would set up the necessary model runs with the required data bases. The user would be relieved of most of the detailed computer steps involved. This approach is particularily attractive since a range of models could be made available to the user under the same front-end system. This would greatly increase the probability that the user would leave the system with a satisfactory answer to his problem. In addition, the technique would provide a centralized outlet for the many models already developed (as well as future models).

A good starting place for front-end development is to look at the expert systems work being done by the artificial intelligence community, for example, Charniak et al. (1980), Rauch-Hindin (1983), and Kinnucan (1984). These systems are meant to mimic the thought processes of some expert in a particular field during problem solving. A similar approach could be used in a somewhat expanded context to include various approaches, simulation models, and data bases in a special expert system or front-end designed to solve problems in agriculture. This system would include the contributions of many experts since soil-plant management is multidisciplinary.

LISP is the computer language used in most artificial intelligence applications. The language is mostly nonnumerical and oriented toward manipulation of character strings and files with alphanumeric information. Some combination of this (or similar) language with FORTRAN 77 would probably be the best way to develop an expert system for agriculture.

FORTRAN 77 now contains much improved methods for dealing with character strings and random access data bases, and most existing FORTRAN programs can run using FORTRAN 77 without major

modification.

As an example use of this system, a user might enter the model from his farm via a time-share terminal and indicate that the corn crop in field X shows a poor stand and yellow color. The model would then respond with appropriate questions about the soils and management for that field. If the farmer could not provide enough soils information, an appropriate data base could be utilized. The expert system would then anaylze the problem using a combination of program logic and simulation to identify the cause(s) and suggest a range of possible solutions. The results would be displayed in terms of yield response and costs associated with the remedial actions which might be taken. The model could also suggest changes in management to avoid or minimize the problem in the future.

The range of agricultural (and other) problems which could be addressed by this technique is limited only by the state of existing knowledge in the subject area and the size and speed of the computers. Existing simulation models such as NTRM, EPIC, and GOSSYM could provide the core for simulation analyses in the expert systems. A major subsystem needing development is a module to converse with the user in English and determine the problem. A few existing interactive models such as COFARM, (Shaffer et al.) and FLEXCROP (Halvorson and Kresge 1982) already interact with the user on this level. The combined use of technology available in the research/engineering simulation models, user-friendly input-output packages and efficient algorithms, and general procedures for artificial intelligence would be an excellent starting place for an expert system in agriculture.

SUMMARY

Simulation models provide the key to integrating the complex physical, chemical, and biological processes associated with soil-crop management. These models require an interdisciplinary approach and must be adequately developed and validated. A broad range of models is emerging from the various modeling groups which offer many possible applications at different levels. These include research, engineering, teaching, and direct access by the general public. Making these applications happen at an accelerated rate will involve patience by administrators, better coordination of data bases, and the development of improved delivery systems for the information the models can supply. In the latter case, the use of an expert systems approach to create front-end modules for groups of simulation models may have some merit. This technique would allow users to run existing models by telling the system what type of problem they are trying to solve, rather than trying to decide how to run the model(s).

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SCS OVERVIEW ON SPATIAL AND TEMPORAL VARIABILITY

Samuel W. Robbins[1]

This topic is an unusual subject for the SCS field hydraulic engineer to address. The subject never comes up in the discussions we hold among ourselves and our clients. It is not that variability of our model input parameters does not concern us. It is simply the fact that we have become accustomed to accepting the variability and the errors our assumptions cause.

It has been and will continue to be the practice of SCS to carefully consider the cost of an improvement in a model used before implementing it. The cost of considering spatial and temporal variability above that already imbedded in SCS models is presently perceived as too high. As technology advances, it is likely that inclusion of new procedures to incorporate variability of spatial and temporal data will be included, but it will be done without substantially increasing data collection or computation costs.

The previous paragraphs represent my views of the present attitudes and future direction of modifications in SCS modeling. These conclusions are significantly affected by the constraints imposed by personnel and funding. The hydraulic engineers in leadership roles have identified many needs for improvement in SCS water resources models which will be made as funds and personnel are available. Any spatial or temporal variability considerations will be included in this list, but the underlying thought in this overview will be that these changes will not be allowed to impose significantly more data collection workload on field personnel or require substantially more cost for computation.

To complete this exercise it is important to be more specific about the present level of spatial and temporal variations in SCS models. The SCS has several water resource models, but I will discuss only two--TR-20 and WSP2. These are a storm event model and the steady-state water-surface-profile model, respectively. These models are presently the most complete water resource models the SCS field hydraulic engineer uses. A discussion of some of the input parameters in these models will give an overview of the existing level of spatial and temporal variation.

SOILS

Soils are assumed to be uniform for an area that has been mapped as a certain type. If two or more soil types are present in a hydrologic unit, they are weighted along with the hydrologic cover characteristics to determine a lumped runoff parameter (runoff curve number).

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Temporal variation of soils is ignored except in rare instances. Cover, land used and cover condition are jointly considered in TR-20. Each land use and condition has been assigned a runoff curve number for each of four soil categories. The spatial variation of land use is lumped by weighting land use according to area, usually also considering soil and hydrologic condition. The soil and land use can be assessed with some precision and is reproducible within reasonable limits, but the condition assessment is a subjective determination and generally not reproducible. All three of these spatial variables are lumped to estimate one runoff curve number for hydrologic unit. Spatial variation can be considered by subdivision of the hydrologic units, but subdivisions can produce computational problems if areas are too small.

Temporal variation of cover definitely occurs on both the short term (seasonally) and the long term (years). The short term variations played a part in the development of runoff curve numbers, but only one number is used and long term variation can only be considered by successive model runs.

RAINFALL

Spatial variability is considered in a gross manner by use of an areal adjustment. The result of this adjustment is to reduce the volume of rainfall with increasing area, but the rainfall is considered uniform over the entire area. Procedures exist for estimating simple areal distributions of the rainfall, but they would be valid for only one event. Time and funds usually permit use of only one pattern. Therefore, the normal procedure is to consider the rainfall uniform.

Temporal variability of rainfall is one of the few areas where TR-20 accommodates variability of the data. Any rainfall-time distribution can be input. It can be made to begin in various subareas independently and to vary in intensity and duration by subarea. Again, this practice is rare because of data and cost constraints.

HYDRAULIC PARAMETERS

Manning's n value is normally an average for a segment. A cross section can be divided into a maximum of five segments. If the cross section has more than five segments with different n values, then the user lumps the most similar segments and develops an n value either by a weighting process or a subjective estimate.

All hydraulic parameters are considered uniform for the entire reach between cross sections. This spatial limitation can be overcome by including many cross sections, but, as always, cost of data collection and processing inhibit carrying this to an optimum; and the user normally lumps in an upstream-downstream direction

much as he does laterally. Flows in WSP2 are steady, but nonuniformity is permitted.

CONCLUSIONS

These examples are only a few of the spatial and temporal variations encountered in hydraulic and hydrologic activities that SCS engineers and technicians confront or ignore. They are adequate to illustrate that the constraints of personnel time and cost of data collection and processing have caused us to lump or standardize almost all variation. Research needs exist and, even if the present constraints inhibit model enhancement, several areas of research can be addressed. Some of these are:

1. Lumping variation introduces error. It would be useful to know the extent of this error and the cumulative effect of the errors.

2. An equal consideration is knowing which assumptions generate the most significant error.

3. When these problem areas are identified, ways to at least partially overcome them can be explored within the limitations presented by cost and time.

4. Constraints of cost may eventually be reduced through developments in computers and data collection (for example, remote sensing and GIS). Advances in these areas will permit progress beyond those in items 1 through 3. Progress will be random if items 1 through 3 are avoided, however.

AN OVERVIEW ON VARIABILITY IN HYDROLOGY

R. E. Smith[1]

One might characterize the recent history of scientific hydrology by conceptually considering it in three phases. The first and presumably early phase would include the research approach which considers the catchment processes to be not only complex in variability but also deterministic in only conceptual (black box) ways, and it would best be symbolized by the unit hydrograph. The second phase would include those research efforts which assume the catchment response to be composed of an array of physically based processes, such as surface water dynamics and unsaturated flow and seeks analytically to take the catchment apart, so to speak, into simpler, mathematically describable functions. The third phase, into which I would place much current research, recognizes that while phase 2 begins the real scientific analysis of hydrology, the catchment is still composed of variability and complexity, and accurate representation of nature requires application of hydrodynamics somehow within a quite complex and variable world.

Characterizing that real world for application of hydrodynamics is the challenge of the treatment of variability. The variability of concern to hydrology includes two broad categories, within which there are two important types of variability: spatial and temporal.

The first category is input variability--precipitation, primarily, although companion inputs to more general ecological/hydrological models must include temperature, solar radiation, wind, and/or other climatic variables. We are accustomed to admitting this class of variability, in general, although sampling limits often force us to treat rainfall as spatially uniform simply because we have one gauge. Furthermore, we are often severely crippled in applying our best tools for runoff prediction because we only have daily rainfall records. This severe time-scale limitation on our knowledge of the variability of input handicaps application of current knowledge. Even worse, daily records do not indicate how many storms might have occurred in that period. Consideration of small, field-scale hydrology is not generally hampered by ignoring spatial variation in rainfall, but larger catchment studies such as those often of concern to the SCS can be seriously handicapped by lack of information on spatial variability of rainfall, including storm cell size and spacing, motion of the storm, and other aspects of time and spatial variability.

The second category of variability is that concerning the catchment properties affecting its hydrologic response. This category also contains both spatial and temporal types of variability.

The spatial type includes geomorphic and spatially dependent stochastic shape properties of surfaces, rills, and channels. In tilled fields, this property also contains a deterministic aspect when runoff follows furrow marks. In undisturbed areas, the geology and vegetation often exert control on surface shapes.

Soil properties also vary in space in relation to the soil-forming mechanisms and runoff patterns, and a variable degree of spatial dependence is often found in hydrologic soil properties (infiltration). Soil water content and vegetation state are two important hydrologic properties that vary not only in space, but also in time, from day to day or season to season. Again, characteristic of much natural phenomena, spatial and temporal correlation dependence complicates the description of variability. Variability between flow paths and variability along water flow paths often have very different effects and significance.

Finally, an overview of variability must consider the question of scale. Differences between runoff on similar plots at different locations in a catchment are expected to exhibit a variability far different from the variation among similar 1,000-acre watersheds (under the same storm). In general, larger scales exhibit averaging effects from their internal complexity. Likewise, the effect of spatial variation of rainfall depends on the relative scale of the catchment and the scale of the storm or storm front. Soil variability also exhibits a characteristic scale, including a dependence scale, above which samples of the "same" soil are uncorrelated in space.

There are at least two approaches to treatment of spatially variable catchments, and they are not conflicting or alternate methodologies. One method is to expand the complexity of the model used until all measured variability can be simulated. Exercise of this method can lead to the second method, which is the analytic treatment of variability by physically useful parameters operating in the context of the physical relations involved. An example of this is the use of geomorphic descriptors such as bifurcation ratios or other network parameters in developing streamflow response to rainfall (Rodriguez-Iturbe and Valdes 1979). There remains much work to be done in the area of joint probabilistic and physical descriptions of the hydrology of natural landscapes.

In closing, it should be emphasized that consideration of variability in current hydrologic models is far more limited by our knowledge of the actual variability of a parameter in nature than by the capability of our models. Expansion of most current physically based simulation models to treat all types of variability is merely a programming problem. The real limit is the gathering of data to describe the existing variability, and then enough samples to begin to be able to characterize expected variability in terms of probability distribution parameters. When this has been accomplished, integration of those parameters into deterministic models, which now must assume a simpler world, can begin to take place.

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HYDROLOGICAL CHARACTERIZATION OF WATERSHEDS

M. L. Sharma and A. S. Rogowski[1]

INTRODUCTION

Quantitative knowledge of soil properties within a watershed is required for prediction of hydrologic behavior. The choice of an approach will be dictated by the magnitude of spatial variability and the distribution of hydrological properties. Which properties should be measured, what sample volume of soil should be taken, what locations and what sampling frequency should be considered are some of the aspects which need to be resolved when characterizing a watershed. Of prime importance in this context is the objective and the desired accuracy for which hydrologic predictions are needed; this will influence the level of sophistication and detail at which a watershed is sampled and data analyzed.

One source of data on soil properties is soil classification. Soil classification is based on the premise that soil properties vary in space. Soil surveys are then used to identify and delineate the soil boundaries. But in most classification schemes these boundaries remain imprecisely defined. The soils of a watershed are grouped into soil series, emphasis being placed on profile variability. The soil survey classification is based on the broad morphological features of the landscape correlated to sampled profile properties such as color, horizon, depth, structure and texture. However, the extent and nature of variability within a soil unit and mapping purity are not always recorded. As a first approximation properties of these soil series may be used in hydrologic modeling. However, it must be realized that the criteria used in classifying soils may not coincide with those affecting hydrologic response of an area. Furthermore, appreciable spatial variability in soil hydrological properties has been observed within a soil series (Rogowski 1972, Nielsen et al. 1973, Sharma et al. 1980), and this may affect the areal response (Sharma and Luxmoore 1979). Thus, under many conditions field characterization of watersheds is considered important. For this, field-oriented methods are needed. The methods for quantifying soil hydrological properties should be simple, rapid and reliable so that a large number of measurements can be made. In general, grid or transect sampling schemes are preferred. In this paper, we consider various aspects of such chacterizations, including the analysis of spatial variability.

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ESTIMATION OF SOIL HYDROLOGICAL PROPERTIES

The choice of hydrological properties and the extent of detail of their characterization, depend largely on the objective and the choice of model to be used. For detailed prediction of water distribution within a watershed both in time and space, a physically based deterministic model such as a three-dimensional water flow equation could be used, and this would require detailed knowledge of the spatial distribution of the soil water retention function $\psi(\theta)$ (water potential ψ as a function of water content θ) and the water flow function $K(\theta)$ (hydraulic conductivity K as a function of θ). On the other hand, for predicting drainage flux under flooded conditions, knowledge of the spatial distribution of only the saturated hydraulic conductivity K_s may suffice.

Field measurement of $\psi(\theta)$ and $K(\theta)$ is time consuming and tedious because a large number of measurements are usually required for field characterization. Numerous attempts have been made in calculating $K(\theta)$ from the laboratory measured $\psi(\theta)$ function (Childs and Collis-George 1950, Millington and Quirk 1959, Brooks and Corey 1964, Green and Corey 1973) and also in approximating $\psi(\theta)$ as well as $K(\theta)$ from only a few measurements (Brooks and Corey 1964, Rogowski 1971). For many hydrologic purposes, the exact shape of these functions may not be important. Using the Brooks and Corey approach, Russo and Bresler (1980) computed $\psi(\theta)$ and $K(\theta)$ from the field measured parameters, K_s, S (sorptivity), ψ_e (air entry value) and θ_i and θ_s (water content of dry soil and at saturation respectively). This procedure enabled rapid determination of approximate $K(\psi)$ and $\theta(\psi)$ for evaluating spatial variability.

Considerable effort has also recently been made in developing empirical methods to estimate hydrological properties based on particle size analysis data. Broad scale hydrological classification of agricultural soils of the United States is being attempted by estimating parameters appropriate to the Brooks and Corey model of water retention (Rawls et al. 1982) as well as parameters suitable for use in the Green and Ampt infiltration equation. In the absence of soil hydrologic data, these approaches are likely to have a wide appeal since they are usually based on readily available information. The limitations of such approaches should however be realized, particularly for soils with predominant structural features (swelling and shrinking clays, soils with large number of macropores, stony soils), and the extent of applicability of such simple methods must be investigated to avoid their misuse.

ANALYSIS OF SPATIAL VARIABILITY

Extent of Variability

The soil system is extremely complicated and highly variable at a scale of the individual primary particle, but such complexity is

bypassed by measuring hydrological properties at much larger scales. Usually the variance for a property decreases with an increase in the volume of the sample (fig. 1). The smallest volume above which the variance no longer decreases significantly defines the representative elementary volume (REV) of a soil for that property (Bear 1972). This is a theoretical concept, and in real world situations, it may be difficult to define. Ideally, the representative elementary volume should encompass components of variability at several scales. In practice, however, hydrological properties are measured on much smaller samples and are considered points of a continuum.

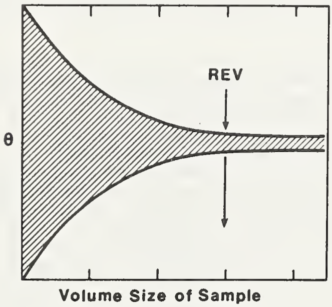

Figure 1.--Schematic representation of variation in the volumetric water content θ of a soil as a function of sample volume. The representative elementary volume (REV) for θ is shown.

For comparative purposes, the magnitude of variability is often represented by the coefficient of variation (CV). It is found to be the highest (CV > 1.0) for transport coefficients (hydraulic conductivity and diffusivity), medium (CV ≡ 0.15-0.5) for properties such as water contents at selected water potential, and least (CV < 0.15) for properties such as bulk density, total porosity (Warrick and Nielsen 1980).

The variability of a property can also be described by the probability density function (PDF), which contains information not only about the averages (mean, mode, median) but also about their moments, and these permit estimation of confidence limits for the property. Identifying the appropriate PDF for a parameter has important implications in computing the number of observations required to estimate the mean with a specified precision (Rogowski 1972, Sharma 1983) and in determining the integrated hydrologic response of an area (Sharma and Luxmoore 1979, Warrick and Amoozegar-Fard 1979).

The higher CV values are usually associated with a larger skewness in the PDF. Properties exhibiting larger CV (> 0.40) are frequently found to have a log-normal distribution, while those with lower CV (< 0.40) may be adequately fitted with a normal function (Rao et al. 1979).

Spatial Dependence of Properties

In the traditional analysis of variability, properties measured within a watershed are assumed spatially independent of each other, and the observations are represented by their mean, standard deviation, and an assumed (or estimated) PDF. The assumption of spatial independence, at least for points close by, seldom holds. Geostatistical techniques (Journel and Huijbregts 1978) can then be employed to evaluate spatial dependence. The spatial dependence of neighboring observations of a property measured as a function of a distance vector h is expressed by the semivariogram $\gamma(h)$:

$$\gamma(h) = \frac{1}{2N} \sum_{i=1}^{N} [Z(x_i) - Z(x_i+h)]^2 \tag{1}$$

where N is the number of pairs $[Z(x_i), Z(x_i+h)]$ for a particular distance (or time) increment h. Thus a semivariogram describes the average rate of change of γ with distance (or time) and shows the variance structure of observations. These observations may or may not follow any type of probability density function; they must, however, for application of stationary geostatistics, be additive (Journel and Huijbregts 1978, p. 199).

There are several theoretical models for $\gamma(h)$ which bear the same relationship to experimental $\gamma(h)$ as a theoretical probability density function does to an experimental histogram (Clark 1982). An idealized semivariogram is shown in figure 2. Numerically the sill (C) usually approaches the a priori sample variance, while the range (a) delineates a neighborhood where the variable is continuous. Generally with increasing separation distance h, γ may increase and approach a constant value. This indicates the extent of spatial dependence. If γ continues to increase with increasing h (as is the case with linear models), it means that the extent of the continuity domain cannot be defined from the available observations. Often γ does not pass through the origin at h=0, and has some positive finite value called a nugget effect. A nugget effect usually suggests a spatial structure on a scale smaller than the sampling interval h, and this spatial structure can be delineated by sampling at shorter intervals.

The degree of linear correlation between neighboring observations as a function of separation distance can also be expressed by an autocorrelation function $\rho(h)$ called a correlogram. Provided covariance exists, the $\rho(h)$ can be calculated as follows:

$$\rho(h) = 1 - \gamma(h)/C(0) \tag{2}$$

where C(0) is a covariance at h=0. For second-order stationary conditions $-1 \leqslant \rho(h) \leqslant 1$ (Journel and Huijbregts 1978, p. 32). The autocorrelation function defines a separation distance

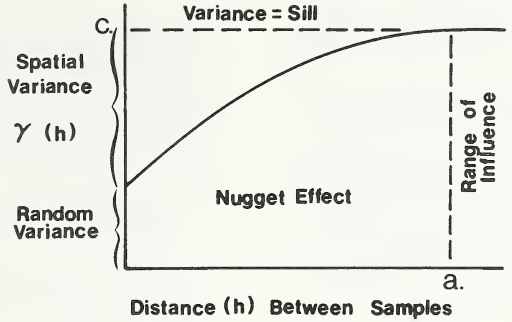

Figure 2.--Idealized semivariogram for a soil property showing sill (C), range (a) and nugget effect.

beyond which correlation between observation pairs is negligible and, thus, a distance beyond which a standard statistical analysis may be employed. It should be noted that essentially the same information is obtained by considering the range of the semivariogram, although in this case the covariance does not have to exist. Once the spatial structure is defined by a semivariogram, the sampling points can be kriged to describe the distribution of a property over an area, in space or in time. The advantage of kriging over other interpolation methods is that in addition to giving the best unbiased estimate of a property distribution over an area, it also provides a value of an estimation variance at each point of interest.

Representing Hydrological Variability by Scaling

Another attractive approach is the use of scaling theory based on the concepts of similar media (Miller and Miller 1956), according to which soil hydrologic variability can be expressed by only one single parameter (Warrick et al. 1977, Sharma et al. 1980). Laboratory studies (Reichardt et al. 1972, Youngs and Price 1981) suggest that this theory could be empirically extended for hydrologically dissimilar media, and as a consequence computation of hydrological properties may be simplified.

For many practical hydrologic considerations, soil variability can be assessed in terms of easily measurable infiltration parameters, S (sorptivity) and K_s (Sharma et al. 1980); and approximate $K(\theta)$ and $\psi(\theta)$ distributions may be computed by using scaling theory (Peck et al. 1977, Sharma and Luxmoore 1979). It is now believed that it is better to characterize variability adequately over an area or in space by a procedure which allows rapid and reliable measurement of a property such as K (at a given ψ), rather than to expand the same energy in getting only a few measurements of the exact $K(\theta)$ and $\psi(\theta)$ functions at a limited number of points.

The theory of scaling was developed from surface-tension-flow considerations based on the concepts of similar porous media (Miller and Miller 1956). It aims at reducing the number of variables; and, thus, it can provide a framework for simplifying the field heterogeneity problem. According to the theory, similar media are scale models of one another and differ only in the magnitude of the characteristic pore dimension, called the characteristic length λ. Strictly soils satisfying similar-media criteria must have identical porosity and the same relative pore size distribution; and this relativity should not change with the degree of saturation.

A dimensionless scaling factor α can be defined as

$$\alpha_i = \lambda_i/\lambda_r \tag{3}$$

where subscripts i and r refer to ith and reference soil respectively. Based on similar-media criteria, water potential ψ and hydraulic conductivity K are scaled as

$$\psi_i = \psi_r\alpha_i \tag{4}$$

$$K_i = K_r\alpha_i^2 \tag{5}$$

It has been shown that with some approximations, the theory can be applied to scale field-measured hydrological properties (Warrick et al. 1977, Sharma et al. 1980) and soil hydrological variability can be expressed by a single parameter, the scaling factor.

For scaling field-measured $\psi(\theta)$ and $K(\theta)$, equations 4 and 5 apply to conditions of identical θ. Owing to the fact that field soils do not have identical porosity (and therefore θ), Warrick et al. (1977) used degree of saturation ($s = \theta/\theta_s$) in place of θ. As a result the variability of data points in the scaled form

of the function was considerably reduced, and ψ and K as a function of s coalesced into relatively narrow bands.

Sharma et al. (1980) demonstrated that the scaling factors can be obtained from infiltration parameters, which can be measured far more easily and quickly. The utility of scaling theory is demonstrated in figure 3. In this case, the cumulative infiltration, I, as a function of time, t, at each of 26 locations in a watershed was adequately approximated by Philip's (1957) two-parameter equation, $I = St^{1/2} + At$, where S is sorptivity and parameter A is related to $K_s (A \simeq 1/3\ K_s)$. Scaling factors based on S and A were calculated as follows:

$$\alpha_{S_i} = (S_i/S_t)^2 \qquad (6)$$

$$\alpha_{A_i} = (A_i/A_r)^{1/2} \qquad (7)$$

Studies reported thus far suggest that scaling theory offers a convenient approach by providing a framework to deal with voluminous data, and thus quantifying the inherent areal variability of hydrological properties in terms of a single physically based parameter. The effect of varying this parameter on the hydrologic response of a watershed can be examined. Such an approach has been developed and used in studying the effect of variability on areal infiltration and drainage (Warrick and Amoozegar-Fard 1979), on water and solute transport (Bresler et al. 1979), and on water balance components of watersheds (Peck et al. 1977, Sharma and Luxmoore 1979, Luxmoore and Sharma 1980).

Most of the studies reported so far indicate that it is necessary to account for spatial variability of hydrological properties and that the areal hydrologic response cannot be predicted by simple average properties. In these studies spatial dependence of the scaling factor (hydrological properties) has not been considered. Incorporation of spatial dependence and evaluating its effect on the areal hydrologic response would be a fruitful research exercise.

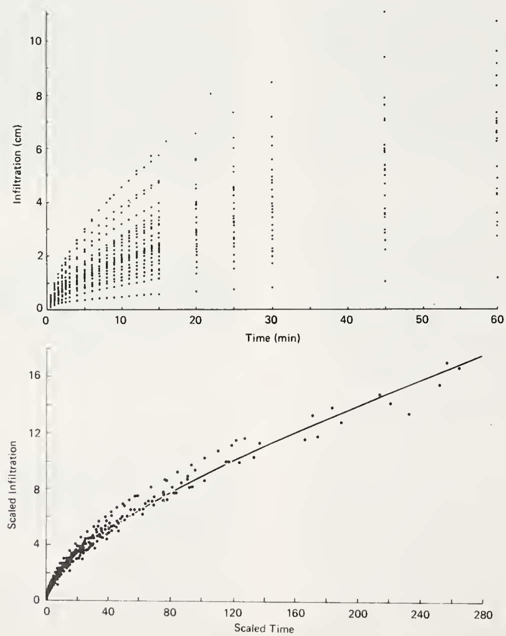

Figure 3.--Plots of field measured cumulative infiltration (I) as a function of time (t) for a watershed (a) in the regional form and (b) scaled form (from Sharma et al. 1980).

SUMMARY

For deterministic prediction of hydrologic behavior, watersheds need to be characterized with respect to soil hydrological properties, and spatial distribution of these properties need to be estimated and accounted for. In this paper we have considered these aspects and demonstrated how scaling theory and geostatistics can be used in the analysis of spatial variability.

Our efforts must continue in developing better methods for characterizing watersheds with respect to soil hydrological properties. The parameters must be measured reliably, rapidly, and with reasonable accuracy. The trade-offs with respect to relevance, convenience, and accuracy must be carefully considered.

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CLIMATE DATA GENERATION

Arlin D. Nicks[1]

INTRODUCTION

Climate data generation models coupled with hydrologic transport models offer great potential as tools to evaluate water resources of a basin under changing land use and management practices. Synthetic data generated by stochastic methods and, hopefully, climatically representative of the geographic area add another dimension to hydrologic model usage other than predicting transport of water, sediment, and chemical loads from a watershed using short measured climatic data records. Generated data provide means to evaluate fixed management and land use over longer periods of time, thus giving estimates of the long-term climatic impact of the management systems, or the data can be used to estimate effects of changing land use and management due to new technology and economic demands.

There have been several climate generation models proposed and developed in the past decade. Two of these have been incorporated into hydrologic (Williams and Nicks 1983, this volume) transport models, SWRRB (Simulation of Water Resources on Rural Basins) and EPIC (Erosion Productivity Impact Calculator (Williams et al. 1982). These models use a daily time step, providing daily rainfall, maximum and minimum daily air temperature and daily total solar radiation. The EPIC generator also gives daily total solar radiation. In addition the EPIC generator gives daily total wind run, and the SWRRB generator provides daily rainfall estimates for up to five subbasin areas. Both models use Monte Carlo methods for generating the required inputs. Both use the same type of random number generator, rainfall occurrence model lag 1 Markov chain for wet-day dry-day sequence selection and both use partitioning of temperature and radiation on wet-dry occurrence (Nicks 1975; Richardson 1981).

These models represent the present state of the art in climate simulation. They are limited to simulaton of daily time steps. Therefore, hydrology models which utilize these generators cannot use infiltration techniques for generation of runoff. Future development of climate generation models should address the problems associated with generating short term rainfall amounts required by infiltration models.

METHODS

Rainfall

The climate generators in SWRRB and EPIC both use the same method to generate daily rainfall. First, the occurrence or nonoccurrence of rain on a day is selected by sampling the monthly distribution of the four-state conditional probabilities of a wet day following a dry day, a wet day following a wet day, a dry day following a dry day, or a dry day following a wet day. Once a day condition wet-dry, dry-dry, and so forth has been chosen, then the amount of rainfall at a point is selected by sampling from a skewed distribution. Parameters required are the 12 monthly values of mean, standard deviation, and skew coefficient of the daily rainfall distribution and the dry-dry and wet-dry transition possibilities at the geographic location at which data is to be simulated. Therefore, 60 parametric values must be input to the simulation model in order to generate daily rainfall.

Temperature

Daily maximum and minimum temperature values are generated using different techniques in SWRRB and the EPIC models. The SWRRB generator uses the normal distribution with a weighting factor calculated from the occurrence of four-state rainfall probabilities applied to a generated standard normal deviate. Also required are the 12 monthly means and standard deviations of maximum and minimum temperature.

The EPIC model uses a simulation technique that is similar to the SWRRB generator, except fewer parameters are required as input. The daily temperature generation is partitioned on wet-day and dry-day occurrences. The required inputs are mean and amplitude values of the Fourier series for wetday mean maximum temperature, dry-day maximum temperature and coefficient of variation of maximum temperature and mean minimum temperature and coefficient of variation for minimum temperature. Maps of these values for the United States have been prepared from which the user can pick values needed for the watershed geographic location. The EPIC generator requires eight parameters.

Solar Radiation

The methods employed to generate daily solar radiation for SWRRB and EPIC are similar to that used for temperature in each generator respectively. Both models restrict maximum radiation to that which can be calculated on a given day by sun position and by season of the year.

TESTING AND GEOGRAPHIC LIMITATIONS

Both models have been tested using observed data from the 134 locations shown in figure 1. The required parameters for the SWRRB and EPIC generators were derived from data tabulations and from maps prepared from weather service data tapes. Both models were then used to simulate 10 runs of 10-year duration to produce 100 years of simulated data at each of the 134 locations. Table 1 summarizes results of these tests. The values shown under columns denoted as "M" and "N" represent the number of times mean monthly

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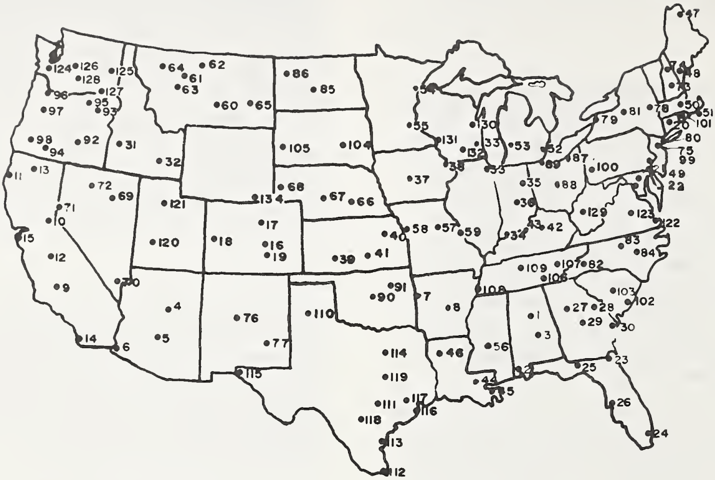

Figure 1.--Distribution of 134 Climate Stations used for SWRRB and EPIC Generators

values were significantly different at p=0.05. In this table, N denotes the comparison using published monthly normal values and M denotes comparison using the mean calculated from the period of records used in deriving the parameters from the weather service data tapes. Often the period mean values and published normals are different and therefore influence the results.

The limitations on using such models are related to the difficulties in obtaining the required parameters. Most of the data required are available only at first order climate stations. Therefore, there are areas of the United States where data points are scarce (see fig. 1). It may be difficult to map required rainfall parameters, such as standard deviation and skew coefficients. Transferring parameters from a map location to a watershed site might be risky, resulting in nonrepresentative data. Both models have their advantages and disadvantages.

The EPIC generator will not generate bimodel solar radiation distributions that are representative of tropical areas, primarily due to Fourier series smoothing of monthly data. Also, the series will not fit temperature and solar radiation data in arctic regions very well. The SWRRB generator requires more parameters as input, and estimates must be made for standard deviation and skew coefficients at locations distant from the stations where these values were derived. Both generators output only daily rainfall data, restricting their use with infiltration type hydrologic modeling.

FUTURE NEEDS

The future research and development needs for climate generation techniques include the following.

1. Improvement of existing models such as those used in EPIC and SWRRB.
2. Development of a short time duration rainfall amount generator.
3. Development of a climatic data base to be used in development and testing of climatic generators.

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Table 1.--Comparison of simulated data runs tested with map parameters (M) and published normal data (N).

STATION	RAIN M	RAIN N	TMAX M	TMAX N	TMIN M	TMIN N	TAVE M	TAVE N	SOL. RAD M	SOL. RAD N
ALBANY, NEW YORK	0	0	2	12	0	11	0	9	3	9
ALBUQUERQUE, NEW MEXICO	0	7	0	9	1	9	2	9	9	12
AMARILLO, TEXAS	0	9	0	9	1	10	1	10	1	10
ASHEVILLE, NORTH CAROLINA	0	2	0	9	2	12	0	12	0	11
ATLANTA, GEORGIA	0	3	0	7	3	9	0	7	0	6
AUGUSTA, GEORGIA	0	6	0	10	1	8	0	8	0	7
AUSTIN, TEXAS	0	3	0	8	0	8	0	9	0	11
BAKERSFIELD, CALIFORNIA	0	10	0	9	2	12	4	12	0	10
BALTIMORE, MARYLAND	0	3	0	12	1	11	1	7	2	10
BATON ROUGE, LOUISIANA	0	1	0	8	0	8	0	8	0	11
BILLINGS, MONTANA	0	7	0	11	1	11	1	8	0	12
BIRMINGHAM, ALABAMA	0	2	0	7	1	10	0	9	0	10
BISMARCK, NORTH DAKOTA	0	5	0	9	2	4	2	5	1	7
BLUE CANYON, CALIFORNIA	0	7	0	12	3	12	5	11	1	11
BOISE, IDAHO	0	7	1	10	0	9	4	8	0	11
BOSTON, MASSACHUSETTS	0	2	2	8	1	11	3	7	0	12
BROWNSVILLE, TEXAS	0	5	0	6	0	10	0	10	0	8
BUFFALO, NEW YORK	0	0	3	11	0	9	3	8	0	8
BURNS, OREGON	0	9	0	8	1	12	3	12	3	8
CARIBOU, MAINE	0	1	0	8	0	9	3	9	3	6
CHARLESTON, SOUTH CAROLINA	0	2	0	9	1	9	0	7	0	9
CHATTANOOGA, TENNESSEE	0	1	0	7	3	10	0	9	0	4
CHEYENNE, WYOMING	1	2	1	12	3	9	0	9	0	11
CHICAGO, ILLINOIS	0	2	3	9	2	12	2	12	1	11
CHARLESTON, WEST VIRGINIA	0	0	0	9	0	9	1	9	2	12
CLEVELAND, OHIO	0	0	1	5	0	8	0	10	3	7
CORPUS CHRISTI, TEXAS	0	5	0	6	12	12	1	11	12	12
COLUMBIA, MISSOURI	0	0	0	7	3	11	1	10	1	6
COLORADO, SPRINGS	0	7	0	9	1	10	0	12	0	11
COLUMBUS, OHIO	0	0	0	4	0	5	2	7	0	7
CONCORD, NEW HAMPSHIRE	0	0	3	8	0	12	3	9	0	10
COLUMBIA, SOUTH CAROLINA	0	3	0	11	3	7	0	11	0	7
DALLAS, TEXAS	0	5	0	6	3	11	0	12	0	10
DES MOINES, IOWA	0	1	1	8	0	5	1	8	2	9
DENVER, COLORADO	0	7	0	10	2	9	2	8	1	11
DETROIT, MICHIGAN	0	0	3	9	2	11	3	6	0	11
DODGE CITY, KANSAS	0	6	0	3	1	8	0	11	0	9
DUBUQUE, IOWA	0	5	2	9	1	7	2	6	1	10
DULUTH, MINNESOTA	0	0	0	11	2	7	3	9	3	9
ELKO, NEVADA	0	7	0	10	0	12	0	12	3	11
EL PASO, TEXAS	0	10	0	8	3	10	12	11	0	7
EUREKA, CALIFORNIA	0	4	0	11	4	10	0	12	7	10
EVANSVILLE, INDIANA	0	1	0	7	0	9	1	10	1	6
FLAGSTAFF, ARIZONA	0	8	0	12	3	12	0	12	4	12
FRESNO, CALIFORNIA	1	11	0	11	3	10	0	11	4	12
FORT SMITH, ARKANSAS	0	4	0	8	2	8	0	9	1	4
FORT WAYNE, INDIANA	0	1	1	8	0	7	0	7	3	9
GALVESTON, TEXAS	2	5	0	12	0	12	0	4	0	11
GRAND RAPIDS, MICHIGAN	0	1	2	10	1	8	2	9	3	8
GRAND ISLAND, NEBRASKA	0	6	0	9	1	6	0	5	1	8
GRAND JUNCTION, COLORADO	0	8	0	10	0	8	0	10	3	12
GREEN BAY, WISCONSIN	0	3	0	7	1	7	1	7	3	8
GREENSBORO, NORTH CAROLINA	0	2	0	6	2	10	0	5	1	7
GREAT FALLS, MONTANA	0	6	0	10	2	7	1	8	3	11
HARTFORD, CONNECTICUT	0	2	1	10	1	12	3	5	2	9
HAVRE, MONTANA	0	6	0	9	2	10	1	9	2	12
HELENA, MONTANA	0	6	0	9	1	12	0	7	1	11
HOUSTON, TEXAS	0	4	0	5	0	3	0	5	0	10
HURON, SOUTH DAKOTA	0	3	0	10	0	7	1	6	1	10
INDIANAPOLIS, INDIANA	0	3	0	7	2	8	2	4	0	8
JACKSONVILLE, FLORIDA	0	2	0	11	0	6	0	7	0	10
JACKSON, MISSISSIPPI	0	1	0	7	0	9	0	7	0	6
KANSAS CITY, MISSOURI	0	4	0	7	2	12	0	7	0	11
KALISPELL, MONTANA	0	3	0	8	1	11	0	10	3	12
KNOXVILLE, TENNESSEE	0	1	0	7	2	9	0	7	1	5
LA CROSSE WISCONSIN	0	1	0	9	1	8	2	9	2	7
LEXINGTON, KENTUCKY	0	0	0	8	0	7	2	8	1	11
LITTLE ROCK, ARKANSAS	0	3	0	8	3	8	0	4	0	8
LOUISVILLE, KENTUCKY	0	1	0	6	0	8	1	11	2	8
LAS VEGAS, NEVADA	0	10	0	12	2	12	4	12	0	12
MACON, GEORGIA	0	3	0	11	0	8	0	9	0	11
MADISON, WISCONSIN	0	2	2	9	1	6	2	8	2	7
MEACHAM, OREGON	0	5	2	11	0	12	1	12	4	12
MEDFORD, OREGON	0	7	0	9	3	12	1	8	6	7
MEMPHIS, TENNESSEE	0	6	0	7	3	9	0	8	1	3
MIAMI, FLORIDA	0	2	0	7	1	11	0	5	0	11
MILES CITY, MONTANA	0	7	0	12	1	8	1	10	1	9
MILWAUKEE, WISCONSIN	0	3	2	10	1	11	2	10	3	8
MILFORD, UTAH	0	9	0	9	0	11	0	11	4	10
MINNEAPOLIS, MINNESOTA	0	2	1	8	1	6	2	8	2	5
MOBILE, ALABAMA	1	1	0	9	0	9	0	7	0	7
MONTGOMERY, ALABAMA	0	3	0	11	0	10	0	9	0	9
MOUNT SHASTA, CALIFORNIA	0	9	0	11	3	12	7	10	1	12
MT. WASHINGTON, NEW HAMPSHIRE	0	12	2	12	3	12	1	12	4	10

Table 1.--continued

STATION	RAIN M	RAIN N	TMAX M	TMAX N	TMIN M	TMIN N	TAVE M	TAVE N	SOL. RAD M	SOL. RAD N
NANTUCKET, MASSACHUSETTS	0	1	1	10	1	12	1	11	3	8
NASHVILLE, TENNESSE	0	5	0	7	1	10	1	4	1	8
NEWARK, NEW JERSEY	0	1	0	6	0	11	2	10	3	8
NEW ORLEANS, LOUSIANA	0	0	0	8	0	12	0	11	0	12
NORTH PLATTE, NEBRASKA	0	7	0	9	2	7	1	9	0	6
NORFOLK, VIRGINIA	0	2	0	10	2	12	0	12	1	5
NEW YORK, NEW YORK	0	1	0	8	1	10	3	6	2	10
OKLAHOMA CITY, OKLAHOMA	0	5	0	10	0	10	0	11	0	7
OLYMPIA, WASHINGTON	0	4	1	11	0	12	4	12	5	11
PENDLETON, OREGON	0	4	1	10	0	12	1	11	4	12
PHILADELPHIA, PENNSYLVANIA	0	1	0	9	0	10	2	8	2	5
PHOENIX, ARIZONA	0	11	0	12	3	10	0	9	6	11
PITTSBURGH, PENNSYLVANIA	0	0	1	5	0	7	3	12	0	7
POCATELLO, IDAHO	0	5	1	9	0	7	0	8	2	6
PORTLAND, OREGON	0	5	0	11	0	12	6	10	3	11
PORTLAND, MAINE	0	0	2	10	2	12	3	9	1	9
PROVIDENCE, RHODE ISLAND	0	1	1	11	1	11	3	7	2	10
PUEBLO, COLORADO	0	5	0	11	0	11	0	8	2	10
RALIEGH, NORTH CAROLINA	0	4	0	10	3	10	0	7	0	7
RAPID CITY, SOUTH DAKOTA	0	3	1	8	2	7	1	10	1	9
RICHMOND, VIRGINIA	0	3	0	12	1	9	1	9	1	12
ROSWELL, NEW MEXICO	0	8	0	12	2	12	0	11	7	11
SALT LAKE CITH, UTAH	0	5	1	7	0	11	4	8	0	10
SALEM, OREGON	0	3	0	11	1	11	3	11	5	11
SAN ANTONIO, TEXAS	0	4	0	8	0	8	0	7	0	10
SAVANAH, GEORGIA	0	3	0	9	0	8	0	7	0	8
SCOTTSBLUFF, NEBRASKA	0	7	1	10	1	8	1	8	0	9
SEXTON SUMMIT, OREGON	0	4	0	11	3	11	1	12	7	9
SHREVEPORT, LOUSIANA	0	4	0	7	0	8	0	8	0	7
SAN DIEGO, CALIFORNIA	0	10	0	12	3	11	0	12	3	10
SAN FRANCISCO, CALIFORNIA	0	9	0	11	3	12	0	11	5	7
STAMPEDE PASS, WASHINGTON	0	4	1	12	0	12	2	12	4	10
SAINT LOUIS, MISSOURI	0	2	0	7	1	10	1	10	1	6
SYRACRUSE, NEW YORK	0	1	3	8	0	7	0	8	3	7
TALLAHASSEE, FLORIDA	0	3	0	9	0	7	0	7	0	7
TAMPA, FLORIDA	0	4	0	11	0	8	0	10	0	9
TOLEDO, OHIO	0	0	2	10	1	10	0	6	2	8
TOPEKA, KANSAS	0	2	0	9	2	8	0	8	0	6
TULSA, OKLAHOMA	0	3	0	10	0	9	0	7	0	10
WACO, TEXAS	0	6	0	8	0	8	0	8	0	11
WASHINGTON D. C.	0	0	0	11	1	11	1	8	2	12
WALA WALA, WASHINGTON	0	3	1	11	0	12	1	12	4	9
WICHITA, KANSAS	0	6	0	10	0	10	1	10	0	11
WILMINGTON, DELEWARE	0	1	0	10	1	8	2	9	1	7
WILLISTON, NORTH DAKOTA	0	3	0	9	2	6	2	8	1	5
WINNEMUCCA, NEVADA	0	9	0	9	1	12	3	12	3	11
YAKIMA, WASHINGTON	0	12	1	11	0	11	3	12	3	11
YUMA, ARIZONA	1	11	2	12	3	12	4	8	2	12

[1] Values listed are the number of months in which the simulated values were significantly different (p=.05) than the published normal mean and the mean from the period of record used.

WEATHER DATA GENERATION

C. W. Richardson[1/]

Both the general climate of an area and the daily variations in weather are of major importance in hydrology. Weather data are one of the primary inputs required by most hydrologic models. The specific weather variables and time resolution that are required vary with the specific hydrologic model that is used. However, weather data requirements that are most common are daily values of (1) precipitation, (2) maximum temperature, (3) minimum temperature, (4) solar radiation, and (5) wind speed. These data are usually obtained from data banks or weather publications. Suitable weather data may not be available for some sites, or the weather record may be too short for meaningful use with a hydrologic model. Solar radiation data are particularly difficult to obtain. Having the capability to generate weather data with the same statistical properties as actual weather for a site offers an attractive alternative to actual weather data. This paper describes a procedure that can be used to generate weather data at an arbitrary site.

MODEL DESCRIPTION

The weather generation procedure is called WGEN. The details of the procedure are given by Richardson (1981) and Richardson and Wright (1983). The procedure will be briefly summarized here.

Daily values of precipitation (p), maximum temperature (t_{max}), minimum temperature (t_{min}), solar radiation (r), and wind speed (v) are generated with WGEN. Precipitation and wind speed are generated independent of the other variables. Maximum temperature, minimum temperature, and solar radiation are generated conditioned on the wet or dry status of the day.

Precipitation

A first-order Markov chain is used to generate the occurrence of wet or dry days. The probability of rain on a given day is conditioned on the wet or dry status of the previous day. A wet day is defined as a day with 0.2 mm of rain or more. The parameters that must be defined are the (1) probability of a wet day on day i, given a wet day on day i-1 [$P_i(W/W)$], and (2) probability of a wet day on day i, given a dry day on day i-1 [$P_i(W/D)$].

Several probability distribution functions have been used to describe the distribution of precipitation amounts on wet days (Woolhiser and Roldan 1982). The EPIC model (Williams et al. 1982) used a skewed normal distribution to generate daily rainfall amounts. The two-parameter gamma distribution is used in WGEN and will be described here.

The density function of the two-parameter gamma distribution is given by

$$f(p) = \frac{\beta^{\alpha}\, p^{\alpha-1}\, e^{-\beta p}}{\Gamma(\alpha)}, \qquad p > 0 \tag{1}$$

where α and β are distribution parameters and $\Gamma(\alpha)$ is the gamma function of α. The α and β are shape and scale parameters, respectively.

The values of P(W/W), P(W/D), α, and β vary seasonally for most locations. In WGEN each of the four precipitation parameters are held constant for a given month but are varied from month to month. The values of each of the four parameters have been determined by month for numerous locations in the United States and are given in Richardson and Wright (1983).

Temperature and Solar Radiation

The procedure that is used in WGEN for generating daily values of t_{max}, t_{min}, and r is that described by Richardson (1981). The procedure is based on the weakly stationary, multivariate generating process given by Matalas (1967). The procedure is designed to account for the persistence (serial correlation) of each variable and the cross correlation among the variables. The seasonal and spatial variations in the correlation coefficients were found by Richardson (1982) to be relatively small. In WGEN the small variations are neglected and the average values of the correlation coefficients given by Richardson (1982) are used. The Matalas (1967) procedure is used to generate new sequences of the residuals of t_{max}, t_{min}, and r that are serially correlated and cross correlated. The final daily generated values are determined by adding a seasonal mean and standard deviation to the residual elements. The means and standard deviations are conditioned on the wet or dry status of the day as determined from the precipitation component of the model.

The means and standard deviations of t_{max}, t_{min}, and r have been determined for many locations in the United States. The seasonal patterns in the means and coefficients of variation have been described by Fourier series, and the Fourier coefficients have been mapped and are given by Richardson and Wright (1983).

Wind

The wind component of WGEN provides for the generation of daily values of mean wind speed. Daily wind speed may be related to the daily temperature, solar radiation, or precipitation values. However, in WGEN the correlation between daily wind speed and the other variables is assumed negligible, and wind speed is generated independent of the other variables. Wind speed is generated using the two-parameter gamma

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distribution. The parameters may be defined for a location on a monthly basis using the mean monthly wind speeds given in the "Climatic Atlas of the United States" (U.S. Department of Commerce 1968) and the procedure given by Richardson (1983).

EXAMPLE

The procedure for generating the daily weather variables will be illustrated by generating a 30-year sample of weather data for Columbia, MO. The precipitation parameters were obtained from a 20-year sample of rainfall data for Columbia. The temperature and solar radiation parameters were obtained from maps given in Richardson and Wright (1983). The wind parameters were obtained from the "Climatic Atlas" (U.S. Department of Commerce 1968).

The generated data and the actual data are compared in table 1. The mean precipitation amount for each month and for the year from the generated data are very similar to that obtained from the observed data. The mean daily maximum and minimum temperatures and solar radiation from the generated data are also about the same as that from the observed data for all months. None of the differences in the means of the observed and generated precipitation, temperature, or radiation data were significant (5 percent level). The mean monthly wind speeds from the generated data are shown in table 1 to compare favorably with that from the observed data.

More extensive comparisons of actual data and data generated with WGEN can be found in Hanson and Richardson (1983) and in Richardson and Wright (1983).

SUMMARY

WGEN can be used to generate daily weather variables that are required for various hydrologic models. The generation procedure produces daily values of precipitation, maximum temperature, minimum temperature, solar radiation, and wind speed that approximate the actual weather for a site.

Application of WGEN to a particular site requires that the generation parameters be determined. The precipitation parameters have been defined for many locations, and the temperature and radiation parameters have been mapped for the United States. The wind speed parameters may be obtained from the "Climatic Atlas of the United States" (U.S. Department of Commerce 1968).

Table 1.--Average precipitation amount and mean daily maximum temperature, minimum temperature, solar radiation, and wind speed by month from data generated with WGEN and from actual data, Columbia, MO

Month	Precipitation amount, mm		Max. temp. °C		Min. temp., °C		Solar rad., ly		Wind speed, m/sec.	
	Observed	Generated	Observed	Generated	Observed	Generated	Observed	Generated	Observed	Generated
Jan.	35.8	32.2	3.4	4.2	-6.8	-6.2	186	193	4.7	4.7
Feb.	42.7	42.7	6.2	5.5	-4.3	-5.3	261	258	5.3	4.7 1/
Mar.	63.7	75.4	10.9	9.9	-0.3	-0.9	348	343	5.5	5.4
Apr.	92.2	86.4	19.0	17.7	7.0	6.5	440	452	5.1	5.3
May	113.0	104.6	24.3	24.0	12.4	12.4	531	541	3.8	4.1
June	105.4	121.7	28.9	30.4	17.4	17.7	571	581	4.0	4.2
July	100.3	112.5	31.5	32.1	19.7	19.6	584	578	3.7	3.6 1/
Aug.	72.1	79.7	30.8	30.6	18.7	18.1	523	516	3.3	3.6 1/
Sept.	101.6	100.1	26.9	25.6	14.2	13.4	427	403	3.6	3.7 1/
Oct.	79.2	85.3	20.7	18.8	8.2	7.0	322	287	3.8	3.4 1/
Nov.	40.1	43.9	12.3	11.6	1.2	0.5	212	207	4.4	4.4 1/
Dec.	42.2	47.2	5.6	6.7	-3.9	-4.0	161	153	4.6	5.1 1/
Annual	888.5	931.9	18.4	18.1	7.0	6.5	381	377	4.3	4.3

1/ The generated mean is significantly different from the observed mean at the 5 percent level.

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DISAGGREGATION OF DAILY RAINFALL

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J. S. Hershenhorn[1]

INTRODUCTION

Simulation models, including components describing the hydrologic cycle, soil erosion, sediment and chemical transport, crop productivity and the effects of various management activities on these processes, have become important tools in management of our land and water resources. The inputs driving these models include rainfall, solar radiation, maximum and minimum daily temperature and, in some cases, wind run. Although many models have options that allow the use of input information for time periods shorter than 1 day, these options are rarely used because of the difficulty in obtaining and using short-period or "break-point" rainfall data. This problem is also a major obstacle to adopting runoff estimation procedures based on infiltration theory (Brakensiek et al. 1981).

One practical way to provide short period rainfall data is to develop a parameter efficient method of disaggregating daily rainfall into individual storms and to disaggregate the rainfall from significant storms into short period intensities. This paper presents a brief progress report on a pilot project designed to assess the feasibility of daily rainfall disaggregation models.

THE PRECIPITATION PROCESS

The rainfall process is defined as the stochastic process $\xi(t)$, $0 < t < \infty$, where $\xi(t)$ is rainfall intensity. A storm period is defined as any time interval when $\xi(t) > 0$. Thus, for any day in which precipitation occurs, we can identify the possible cases shown in figure 1.

We will designate the total rainfall on day j as X_j and the amount of precipitation in the i^{th} complete storm on day j as Y_{ij}. The amount of the i^{th} partial storm on day j is Y_{pij}. The duration of the i^{th} complete and partial storm is D_{ij} or D_{pij}, respectively. The time of ending of the i^{th} complete storm is τ_{ij}. Obviously,

$$\sum_{i=o}^{C_j} Y_{ij} + \sum_{i=o}^{N_j} Y_{Pij} = X_j \tag{1}$$

where $Y_{oj} = Y_{poj} = 0$, C_j equals the number of complete storms and N_j is the number of partial storms on day j.

A flow chart of the daily disaggregation process is shown in figure 2. The objective of this research is to devise a procedure to simulate the number, amounts, and durations of complete and partial storms, given only the amount of daily rainfall on day j and day j + 1. Further disaggregation is then used to determine the intensity patterns within significant storms.

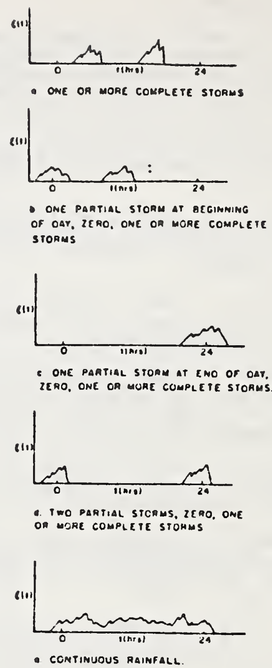

Figure 1. Possible realizations of rainfall process within a day.

ANALYSIS OF DATA

Breakpoint data for raingage 5, at the Walnut Gulch experimental watershed in southeastern Arizona, were used in this pilot project. The record length is 23 years, and only data from the months of July and August were used. We assume that the disaggregation process is stationary during this portion of the summer rainy season. Storms were defined as any period in which rainfall intensity was > 0 or did not equal zero for longer than 10 minutes.

The data were first separated into three files: (1) days with only complete storms, (2) days with one partial storm, and (3) days with two partial storms. Days were broken at midnight. As yet, we have studied only the first data set.

The first step in disaggregation for a day with only complete storms is to generate the number of storms, C_j, given the amount of rainfall X_j(see fig. 2). We found that the geometric probability mass function with a mean dependent on X_j gave a

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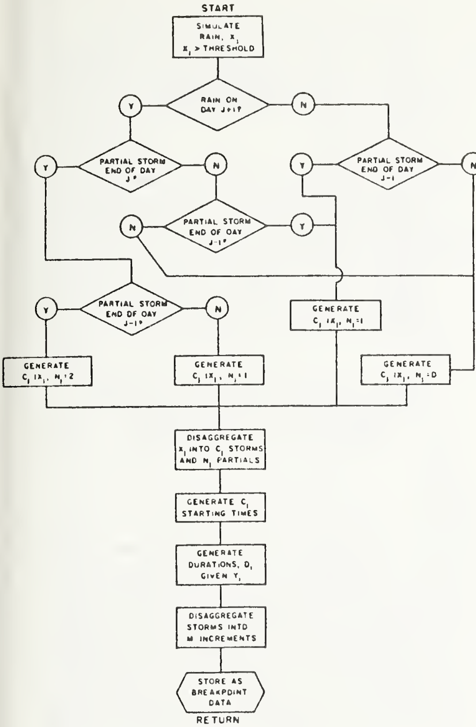

Figure 2. Flow chart of daily rainfall disaggregation.

very good fit to the data. Thus, the joint cumulative probability function can be written as

$$P\{C_j \leq n, X_j \leq x\} = F\{n,x\} = \sum_{i=1}^{C_j} \int_o^x (a_1 + b_1 x)^{-1}$$

$$[1-(a_1 + b_1 x)^{-1}]^{n-1} \{\frac{\alpha e^{-x/d}}{d} + \frac{(1-\alpha)e^{-x/\theta}}{\theta}\} dx \quad (2)$$

if the marginal distribution of daily rainfall is a mixed exponential with parameter set (α, d, θ) (Woolhiser and Roldan 1982).

Time Distribution of C_j Storms

Empirical distribution functions for the time of storm beginning, $\tau_{ij} - D_{ij}$, were calculated for days with one storm, two storms, three storms, four storms, and for all storms. If we assume that the storm times are independent and identically distributed, the distribution function of the time of the first storm, the time of the second storm, et cetera, can be obtained from the order statistics.

For example, if $F(\tau^*) = P\{\tau - D \leq \tau_*\}$, and if we consider days with two storms, the distribution function of the first storm is

$$F(\tau_1^*) = 2F(\tau^*) - F(\tau^*)^2 \quad (3)$$

The empirical distribution functions of the times of first and second storms during a day are compared with functions calculated using order statistics in figure 3. It appears that the assumption of independent, identically distributed storm arrival times is acceptable.

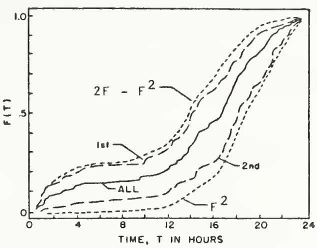

Figure 3. Distribution functions of time to beginning of storms (two storms per day).

Joint Distribution of Storm Duration and Amounts

After individual storm amounts have been obtained by disaggregating the daily total into C_j storms, it is then necessary to assign a duration, D_{ij}, to each storm amount, Y_{ij}. It has been found that D_{ij} and Y_{ij} are jointly dependent and, for 242 storms with $Y \geq 0.25$ inch, are best described by a joint distribution consisting of an exponential marginal distribution of storm amount, Y, and a log-normal conditional distribution of D, given Y. The dependence is specified by the linear relation

$$E\{\ln D \mid Y\} = a_2 + b_2 Y \quad (4)$$

For the marginal distribution of Y, the exponential distribution was superior to the mixed exponential, log normal, and Kappa III distributions. The log-normal conditional distribution was superior to the Weibull disbribution.

Disaggregation of Storm Rainfall

Let us consider the ν^{th} storm in a sequence, beginning at time τ_ν^*, and ending at τ_ν. The total amount of precipitation for this event is

$$Y_\nu = \int_{\tau_\nu^*}^{\tau_\nu} \xi(t)dt \quad (5)$$

and the duration $D_\nu = \tau_\nu - \tau_\nu^*$.

Let us define the dimensionless process

$$Y_\nu^*(t) = \frac{1}{Y_\nu} \int_{\tau_\nu^*}^{t} \xi(s)ds \; ; \; \tau^* \leq t \leq \tau \quad . \qquad (6)$$

If ν is fixed,

$$t_\nu^* = \frac{t - t_\nu^*}{D_\nu} \quad ; \quad \tau_\nu^* \leq t \leq \tau_\nu \qquad (7)$$

where $0 \leq t_\nu^* \leq 1$. Thus, the intensity pattern within a storm can be described by the dimensionless stochastic process $\{Y_\nu^*(t^*);\ 0 \leq t^* \leq 1\}$. Possible realizations of this process are shown in figure 4. Let us consider the discrete time process

$$\{Y_\nu^*(\tfrac{k}{m});\ k = 0,\ 1 \cdot \cdot \cdot m-1,\ m\}$$

and define the rescaled increments as

$$Z_\nu(t_*) = \frac{Y_\nu(t_*) - Y_\nu(t_* - \frac{1}{m})}{1 - Y_\nu(t_* - \frac{1}{m})} \quad ;$$

$$t_* = \frac{1}{m} \cdot \cdot \cdot \frac{(m-1)}{m},\ 1 \ . \qquad (8)$$

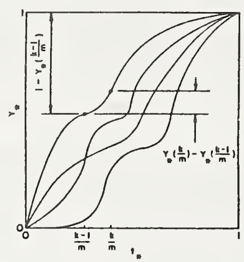

Figure 4. Sample function of the dimensionless rainfall accumulation process $Y^*(t_*)$.

This dimensionless process was divided into 10 equal time increments. An analysis of data for 275 thunderstorms greater than 0.25 inch, at the Walnut Gulch experimental watershed, showed that the sequence of rescaled increments Z_1, Z_2 $\cdot \cdot \cdot$ Z_9 can be represented by a nonhomogeneous first-order Markov Chain. The expected value of Z_k, given Z_{k-1}, is a linear function of Z_{k-1}. The marginal distribution of Z_1, and the conditional distributions of $(Z_k | Z_{k-1})$ $k = 2, 3 \cdot \cdot \cdot 9$ can be adequately described by the beta distribution. The number of parameters in this model can be reduced from 26 to 10 by approximating the two parameters in the conditional expectation function and the conditional beta parameter as polynomial functions of dimensionless time. This represents a significant decrease in numbers of parameters compared with alternative methods, yet does an adequate job of simulating intra-storm intensities. An example of an observed storm hyetograph, along with two simulated hyetographs, is shown in figure 5.

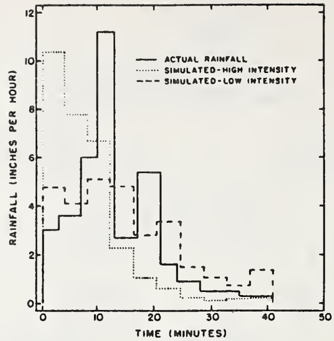

Figure 5. Actual storm of 2.02 inches in 41 minutes with two simulated storms with the same amount and duration.

SUMMARY

A pilot project designed to investigate the feasibility of a stochastic model to disaggregate daily rainfall is described. Significant progress has been made in disaggregating individual storms into rainfall intensities for periods of one-tenth of the storm duration. A logical procedure has been developed for disaggregating daily rainfall into storms, and an appropriate stochastic structure has been identified for several steps of the process. The research described is still underway, so it is possible that alternative distributions may yet be found that are superior to those described in this paper.

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FORECASTING SNOWMELT RUNOFF

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INTRODUCTION

The Soil Conservation Service (SCS) administers the cooperative Snow Survey and Water Supply Forecasting Program in the Western United States. This program is conducted in 11 Western States and provides predictions of seasonal water supplies based on current mountain snowpack and other hydrometeorological conditions. This information is primarily provided to the agricultural community for use in managing farming operations in a manner consistent with projected water supplies.

More than 500 individual streamflow gauging points are now being forecast operationally; drainage areas range from less than 100 square miles to over 100,000 square miles. Streamflow predictions are currently made monthly, January through June, and disseminated via watershed bulletins and State water supply outlook reports to more than 25,000 organizations and individuals.

Major interest groups benefitting from these forecasts include irrigators who derive their water supply from direct diversions or reservoirs, watershed associations, water conservancy districts, reservoir managers, irrigation companies, units of government, water distribution administrators, and hydropower generation facilities. Runoff predictions are generated and issued in cooperation with five river forecast centers of the National Weather Service.

WATER SUPPLY FROM A NATIONAL PERSPECTIVE

Water conservation including water supply is the second highest priority in SCS operations targeting. Accurately predicting seasonal runoff originating from snowmelt is an important component of the overall national effort. SCS has taken several steps recently in an attempt to strengthen and improve its delivery of water supply information to water managers in snowmelt runoff areas. These are (1) reorganization of the snow survey program to place more emphasis on the use of hydrologic process models in a real-time forecasting environment, (2) increase the effort to integrate snow survey technology into other ongoing SCS conservation operations programs, and (3) focus more attention on applying streamflow forecast predictions to individual agricultural operating units.

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SNOW SURVEY REORGANIZATION

Realignment of responsibilities and redistribution of personnel accomplished as part of the snow survey reorganization were intended to provide a number of positive benefits to the overall water supply forecasting effort. These include

1. Improving SCS capability to use existing hydrologic models or modifying them to use SNOTEL and remotely sensed data in a forecast mode.

2. Centralizing data analysis and interpretation functions to capitalize on the synergistic effects of a multidisciplinary staff in one location.

3. Enhancing data base management capabilities.

4. Facilitating interagency cooperation.

5. Standardizing forecast products and improving service to users of forecast information (through increased use of automated data processing and telecommunications facilities).

6. Provide a focal point for technology transfer activities.

7. Creating water supply specialist positions to serve a liaison function between forecasters and users.

Whether these benefits will be fully realized depends largely on the accuracy and timeliness of the forecasts as well as the effectiveness of the dissemination mechanism.

SCS FORECAST PROCEDURES

SCS produces a number of streamflow forecast products for public consumption, including seasonal volume, seasonal peak flow, hydrograph recession, lake level, and seasonal low flow predictions. A combination of statistical and empirical techniques have traditionally been employed to generate these products. However, within the last few years, forecast technology has improved rapidly. Recent technological advancements include

1. Development of automated networks for remote acquisition of data.

2. Availability of tremendous computational power housed in relatively compact minicomputers and microcomputers.

3. Availability of data base management systems to facilitate exchange, storage, and retrieval of large volumes of data.

4. Development of physically based process simulation models which effectively utilize available conventional and remotely sensed data in user selected time steps.

These advancements dictated a reassessment of how forecasts had been produced in the past and a careful evaluation of what implications these changes in technology held for the future.

CURRENT METHODS

The most common technique used by SCS to predict water supplies and hydrograph characteristics is one based on statistical regression concepts. Various types of regression analyses including simple linear, multiple linear, curvilinear, and principle components, have been used to develop forecast equations. Regression procedures have been attractive because they are relatively easy to generate and apply, and require minimum input data compared to simulation models. They are also easily understood and have proved relatively reliable for most types of forecasts. However, hydrologists have long recognized that statistical models suffer from a number of limitations that restrict or prohibit their applicability in many situations.

Regression models are unreliable in extreme years which are outside the bounds of the historical time series used in developing the original forecast equation. They are not easily adaptable to run in short time steps on the order of days. They often do not reliably predict the consequences of infrequently observed hydrometeorological conditions because the streamflow that occurred from those conditions is treated as an outlier and omitted in equation development. The most serious limitation of regression procedures, however, is their inability to provide any insight into physical processes. With water management becoming more complex and the level of competition rising for available water, it was readily apparent that other forecast tools were needed to complement existing procedures.

HYDROLOGIC PROCESS MODELS

An obvious way to meet the need for more flexibility and greater insight into hydrological processes was to employ continuous simulation models in a forecast mode. Selection of the best model(s) was not a simple matter, however. The leading candidates for SCS applications are

1. National Weather Service River Forecasting System (NWS/RFS) (1978).

2. U.S. Geological Survey Precipitation Runoff Modeling System (PRMS), described by Leavesley et al. (1983).

3. Snowmelt Runoff Model (SRM), described by Martinec et al. (1983).

4. U.S. Army Corps of Engineers Streamflow Synthesis and Reservoir Regulation model (SSARR) (1975).

5. Agriculture Research Service Small Watershed Model (SWAM), described by Decoursey (1982).

Other models have been studied but were either very similar to the above or judged not suitable for a variety of reasons.

Many models evaluated by SCS suffer from some or all of the following characteristics which detract from their acceptability for use by SCS.

1. Minimal or no use of actual measured snow water equivalent available daily through the SCS snow survey telemetry (SNOTEL) network.

2. Calibration requiring a lengthy period of record.

3. Complexity of the model and associated preprocessor routines that required a continuing high commitment of personnel and computer resources.

4. Documentation and/or accessibility was inadequate.

5. Transportability between computer systems was questionable.

6. Data to drive the model were lacking for operational application.

7. Minimal or no use of soils and vegetation information.

8. Natural resource impact analysis from management systems is not supported.

Before adopting any of the leading models for operational forecasting, SCS will investigate them further and has enlisted the aid of scientists from ARS, Colorado State University, and U.S. Geological Survey. Cooperative efforts with these agencies and institutions will involve modifying current models to use data obtained through the SNOTEL system. In addition, tests will be conducted on operationally forecasted basins to determine each model's suitability to run in a forecast mode.

FUTURE OPERATIONS

SCS does not believe a single model can adequately address all forecast situations in a cost effective manner. Rather, forecast operations for the future require a family of complementary tools; each model will be applied according to the type of prediction or water supply question to be addressed. A hierarchy of techniques is envisioned ranging from simple empirical relationships to very sophisticated natural resource assessment models that also have forecast capabilities imbedded in them. Regression procedures will still play an important role. Greater reliance will gradually be placed on multicomponent hydrologic process simulation models that incorporate watershed characteristics and effectively use daily SNOTEL data.

RESEARCH TASKS

In the process of reviewing water supply forecast requirements for the future, SCS has identified the following research needs that should be addressed in order to achieve potential benefits accruing from accurate and timely forecasts delivered to the agricultural community:

1. A methodology for applying streamflow forecast information at the farm operator level to maximize productivity and economic returns.

2. A hydrologically sound automated means of incorporating real-time data from short-term record stations into physically based conceptual forecast models.

3. An operationally viable procedure to use remote sensing techniques to monitor snow covered area, snow depth, snow water equivalent, and surface temperature for application in streamflow forecast models.

4. A comprehensive, automated data access and retrieval service for USDA agencies to minimize the high costs of duplicating data bases maintained by other agencies and performing unnecessary manual key entry of published data.

SUMMARY

SCS has been involved in snow survey and water supply forecast activities since the mid-1930's. This program serves a large sector of the economy in the western United States dependent upon snowmelt runoff for its water supply. A reorganization of the snow survey program has been completed to increase capabilities in the area of hydrologic modeling and to provide better and more timely forecasts to water managers. Forecast procedures, although currently based on regression techniques, are going to be supplemented by hydrologic models which take advantage of real-time data collected by the SNOTEL system. SCS is developing a forecasting program which will employ a specific forecast technique dictated by the end applicataion of the forecast from among a hierarchical family of models. Several research needs have been identified associated with water supply forecast operations.

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COOPERATIVE RESEARCH ON WATER SUPPLY FORECASTING

K. R. Cooley and A. L. Huber[1]

INTRODUCTION

The Soil Conservation Service (SCS) and the Agricultural Research Service (ARS) have conducted cooperative projects in various aspects of snow hydrology for a number of years; however, cooperative projects ón water supply forecasting are relatively recent. This report consists of a review of a recent publication and a publication in press, both of which deal with different approaches to water supply forecasting, and a discussion of existing projects.

HISTORICAL REGRESSION EQUATION APPROACH

Historically water supply forecasts have been determined by regression relationships between long-term snow course measurements and observed streamflow. SCS snow course measurements are normally made just prior to the first of each winter month so that a forecast can be published on the first of the month. Forecasts are generally for volume of runoff to be expected at some later period in the spring or summer. Hydrologic forecasting in real time is becoming increasingly important for protecting life and property, and considerable effort has been expended by the Soil Conservation Service and the Bureau of Reclamation to collect real-time snow course data. Real-time water supply forecasts could also provide significant economic benefits to both agriculture and power interests in managing the water resource. A strategy for making seasonal water supply forecasts in real time by utilizing conventional regression-based water supply forecasts has been developed by Huber (1984). A summary of the development strategy and procedure described by Huber using data from Reynolds Creek in southern Idaho (Robins et al. 1965) follows.

Forecasting Equation Development

This step consisted of assembling the historical data for several index and forecast variables using the snow course at Reynolds Mountain. Variables selected for use in the forecast equations were obtained by examining the intercorrelation among all candidate variables as well as their correlation with the seasonal runoff to be forecast. The candidate variables included precipitation, snow water equivalent (SWE), temperature, and antecedent runoff. A screening process eliminated all variables except SWE from the Reynolds Mountain snow course for predicting the runoff. The forecast equations resulting from this process are summarized in table 1.

[1]K. R. Cooley and A. L. Huber, hydrologists, USDA-ARS, Northwest Watershed Research Center, Boise, ID.

Standard Errors of the Forecast Equations

Analysis of variance produced when the regression equations were calculated provided standard error estimates for each equation. Also determined were the standard error of the estimates provided by applying the equations, and the calculated confidence interval about the estimates given by applying a particular equation.

Procedure for Using the Forecast Equations in Real Time

Real-time use of the forecast equations requires that (1) variables in the equations be related to real-time data acquisition system variables, (2) a method of interpolation between estimates made from forecast equations bracketing the real time be established, and (3) confidence intervals about the forecast estimate be determined.

Conventional forecasting equations have been developed from historical data generally collected near the first of the month during the period of snow accumulation, whereas real-time systems collect data continuously. This requires that some concurrent period of measurement exists so that historical data can be related to real-time data. The differences between real-time sensed snow pillow data and the measured snow course data at Reynolds Mountain were very minor for the few instances that direct comparisons could be made. When a sufficient number of concurrent measurements are available, differences will be tested statistically. At other locations, where the snow course and real-time data acquisition site are some distance apart, the relationship between the two must be established and included in the forecast procedure.

It is necessary to interpolate between the values obtained from the conventional equations that bracket the real-time period in order to apply the equations in real time. Linear interpolation was used for the Reynolds Mountain data; however, the situation may vary for other locations, requiring higher order interpolation techniques.

A procedure is developed to determine confidence intervals about the forecast estimate based on a knowledge of the variance of the estimate. An example of this procedure is presented in Huber (1984).

On-line Aspects of the Real-time Procedure

Agency policy largely dictates the final step of user needs. The product could vary from a table of forecasts that can be accessed, to a sophisticated computerized system that could update the regression equations themselves, calculate the variances and covariances desired, and then calculate the confidence interval at any specified probability level.

Table 1.--Prediction equation for Tollgate March-July runoff (inches of water) based on Reynolds Mountain snow course snow water equivalent (inches of water)

Equation date	Regression intercept B_o	Coefficient slope B_i	Degree of freedom DF	SSQ(X) $(X-\bar{X})^2$	Mean (X) $\Sigma X/n$	Standard error S_e	Correlation coefficient r
JAN 1	1.6162	0.7454	15	337.76	8.41	2.0400	0.866
JAN 15	0.3775	0.6768	15	431.53	11.09	1.8691	0.889
FEB 1	-0.1722	0.5630	15	638.04	14.31	1.7851	0.899
FEB 15	-1.1971	0.5613	15	710.84	16.18	1.3195	0.946
MAR 1	-1.1411	0.4904	15	869.71	18.41	1.6507	0.915
MAR 15	-1.499	0.4700	15	946.26	19.86	1.6545	0.914

Tollgate mean runoff = 7.89 inches, 17 observations

From Huber (1984)

HYDROLOGIC SIMULATION MODEL APPROACH

Snowpack accumulation and melt are major factors in both the amount and timing of surface runoff from western rangelands. A review of the literature indicated that numerous snow accumulation and melt algorithms have been developed for use in streamflow simulation models, which generally fit into one of three types. The first and most common type is an empirical relationship normally containing one or two parameters, such as temperature multiplied by a constant (or degree day) concept (Riley et al. 1972). The second type consists of a more fundamental partial or complete energy budget which requires considerably more detailed data sets (Leaf and Brink 1973). The third type is a combination of the other two, in which empirical relationships between readily available air temperature and each flux in the energy balance are developed (Anderson 1973).

A test of the first and third types of simulation models was reported by Huber (1983). A summary of his report, including the models tested and results obtained, follows.

Snow Models Tested

Four of the models are of the first type, that is an empirical relationship, and the fifth model is of the third type, being a combination model.

CREAMS Model

The CREAMS snow model simply allocates and accumulates precipitation as snow when the air temperature is less than 0° C. When the temperature is above 0° C, and snow storage exists, snowmelt occurs.

Generalized Temperature Melt Factor Model

This model, also referred to as the degree-day method, allocates the precipitation and calculates the melt on the basis of the average daily air temperature. The CREAMS model is a special case of this model with a constant melt factor. Generally the melt factor coefficient and the melt threshold temperature are determined by calibrating the model using historical snowpack data.

Potential Solar Insolation Melt Factor Model

In this model, daily average air temperature controlled the accumulation of the snowpack and the occurrence of snowmelt. The actual melt, however, was calculated as a function of the potential solar insolation received at the top of the atmosphere. The potential solar radiation values depend on the time of year and latitude of the site. The radiation melt factors are obtained by calibrating the model with historical snowpack data.

Exponential Decay Temperature Melt Factor Model

This model treats the snowpack as a linear storage reservoir with snowmelt being proportional to the amount of water in storage. A proportionality constant and melt threshold temperature are determined during the calibration process using historical data.

National Weather Service (NWS) HYDR-17 Model

This model considers the significant physical processes governing the accumulation and melting of snow. Each processes is related empirically to the air temperature, precipitation, and elevation or pressure of the site. The accumulation of snow is similar to that of the melt factor models. If air temperature is less than or equal to a threshold temperature, the precipitation is considered to be snow and is added to the existing snowpack; otherwise, it is modeled as rain.

The melt process is divided into that occuring during rain-on-snow and that occuring during nonrain periods, because melt rates are generally

quite different for these two conditions. Rain-on-snow melt is assumed to occur at the snow surface and is computed from an energy balance equation. The melt occuring during nonrain periods is calculated from an empirical temperature-based melt-factor equation similar to the equation in the generalized melt factor model. Groundmelt which occurs continuously at the bottom of the snowpack is also considered. A range of values for the coefficients required are included along with guidelines for their selection.

Testing the Models

The overall objective was to test the ability of the models to simulate the snowpack at a surveyed snow course site. The data used in testing all of the models included daily maximum and minimum temperature, precipitation, and snow water equivalent at the Reynolds Mountain snow course. Each model was first calibrated using 1980 water year data; then, a 4-year test period (1970, 71-72, and 77), including the high and low years of record, was simulated to test the validity of the calibration coefficients. The models were evaluated using an objective function, a bias function, and the product moment correlation coefficient, r, between simulated and measured snow water equivalent (SWE). Summary of the calibration and test period results are given in Table 2.

Each of the models produced a reasonably good estimate of SWE during the 1980 calibration year period. All of the models tested used air temperature to trigger the melt and accumulation processes. Differences, must therefore be attributed to the way the snowmelt is calculated and routed through the snowpack. The simulations for the 4-year test period illustrate a problem common to all of the temperature driven snowmelt models, that is the models predict melt, based on temperature, when in fact accumulation was still occurring (example 1970, fig. 1). This suggests that under certain conditions, the ambient air temperature fails as an index of the physical processes that cause the snow to accumulate and melt. The inclusion of additional variables, such as solar radiation, wind run, and vapor pressure, may be necessary to improve the models. Overall, the algorithm employed in the NWS model most closely matched the measured snow course values during the test period.

EXISTING PROJECT

Under an existing program with SCS, ARS will

1. Continue development of automated procedures to use actual real-time data to generate mid-month (or more frequent) forecasts from existing regression equations.

2. Test a modified version of the NWS model on an operational SCS watershed, including algorithms for (1) snow accumulation and melt, (2) soil moisture, (3) channel routing, and (4) preprocessing of temperature and precipitation to obtain mean areal values.

3. Investigate the possibility of using real-time data to update model outputs.

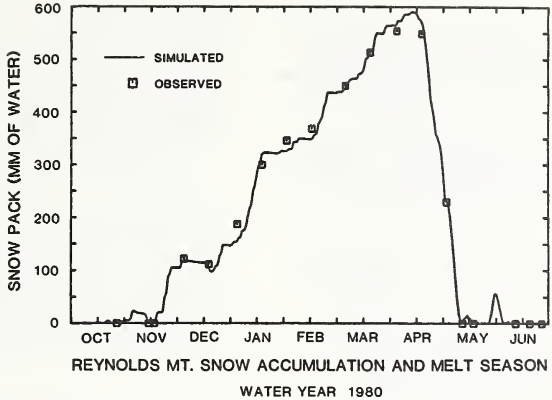
Table 2.--Summary of calibration and testing results for the five snow models being evaluated

MODEL	Calibration period water year 1980: Objective function[1] (mm)	Bias function[2] (mm)	Correl. coeff. r	Test period - (water years 1970, 71, 72, and 77): Objective function (mm)	Bias function (mm)	Correl. coeff. r
ARS-CREAMS	410	-410	0.994	9443	-9189	0.853
TEMPERATURE MELT FACTOR	213	-206	0.997	8240	-7975	0.887
RADIATION MELT FACTOR	130	-50	0.998	11261	-10986	0.741
EXPONENTIAL DECAY	410	-6	0.984	10742	-9990	0.753
NWS HYDRO-17	144	-26	0.998	6824	-6824	0.905

[1]Objective function = $ABS(SWE_{com} - SWE_{obs})$

[2]Bias function = $(SWE_{com} - SWE_{obs})$

From Huber 1983



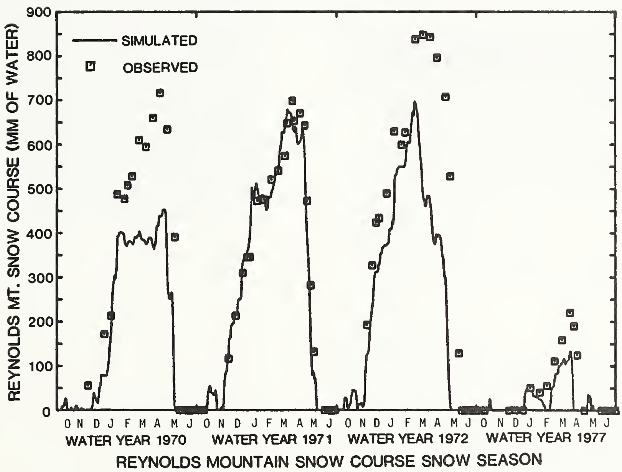


Figure 1.--Snow water equivalent at the Reynolds Mountain snow course for the calibration water year 1980 (above) and the 4 test years 1970, 1971, 1972, and 1977 (below) during the snow accumulation and ablation period. Simulated by the NWS HYDRO-17 model.

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SNOWMELT SIMULATION IN CREAMS2

R. E. Smith[1]

For some purposes, one of the most serious data limitations of CREAMS2 is the inability to distinguish occurrence of actual snowfall within the rainfall data sequence. Such distinction would require at least the reading of detailed actual temperature records. Even this would not guarantee the detection of some snowfalls.

It is somewhat less difficult to estimate the melt of snow from actual or synthetically estimated snow accumulations. Figure 1 illustrates the processes that CREAMS2 considers in estimating the melt and evaporation loss of snow. A certain amount of the snow is intercepted on plant material or standing dry material that may be present. This is subject to rapid subsequent evaporation and/or melt as is intercepted rainfall.

Snowpack evaporation is calculated in a manner similar to bare soil evaporation, by using a modified surface albedo and daily temperature and radiation values. Snowmelt is calculated for two heat sources: air heat convection and soil heat flux. Air melt is estimated using a degree-day method modified by shade and snowpack depth (fig. 2). Pack depth is used as a surrogate for snow heat storage and ripening phenomena. Melt due to soil heat flux can be estimated more straightforwardly. Snow temperature is assumed to be 0°C (conservative), and heat transfer to the snow is reduced by presence of surface residue and mulch. Snowmelt runoff is estimated within unsaturated soil water calculations, considering the current capacity of the soil profile to accept meltwater at the calculated rate, and assigning any excess to runoff. That runoff water is then routed as the particular hydrology option requires.

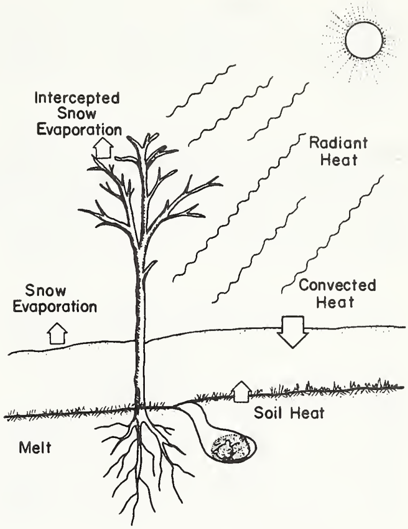

Figure 1.--Illustration of the principal components of snow-mass balance.

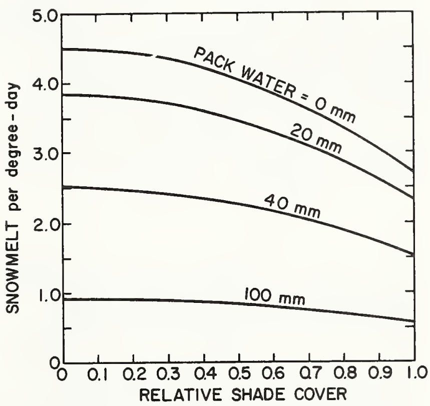

Figure 2.--Snowmelt is modified slightly by the depth of the snowpack and the amount of shade from perennial cover.

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THE SNOWMELT COMPONENT OF THE SPUR MODEL

K. R. Cooley, E. P. Springer, and A. L. Huber[1]

INTRODUCTION

Several of the models used within ARS to predict soil water status, forage yield, or a complete water balance do not have adequate provision to account for snow accumulation and melt. A general model is needed that would handle heavy continuous snow, isolated drifts, or intermittent light snow conditions, in order to expand the use and flexibility of existing and future hydrologic models.

A review of the literature indicated that three main types of snow accumulation and melt models have been developed. The first, and most common type, consists of a variety of empirical relationships generally containing one or two parameters, such as a constant times air temperature concept (Riley et al. 1972). The second consists of the more technically sound partial or complete energy budget approach, which requires considerably more detailed data sets (Leaf and Brink 1973). The third type combines both by developing empirical relationships between readily available air temperature and each flux in the energy balance (Anderson 1973).

The third type was selected for testing because (1) air temperature data are readily available, (2) the approach appeared to be technically sound, (3) the model had been tested in several climatic regions within the United States, and (4) an expected range of values for the calibration parameters was provided for a variety of conditions. After initial tests indicated that the snowmelt model provided adequate results, it was selected for inclusion in the SPUR (Simulation of Production and Utilization of Rangelands) model (Renard et al. 1983).

Description of the Model

The snowmelt model selected was developed by Eric Anderson of the National Weather Service (NWS) and is called HYDRO-17 (Anderson 1973). It is a conceptual model of the physical processes affecting snow accumulation and snowmelt, which Anderson considers significant. Air temperature is used to index energy exchange across the snow-air interface, thus differing from the degree-day method which uses air temperature as an index to snow cover outflow or water leaving the bottom of the snowpack. The degree-day method does not explicitly account for freezing of the melt water due to a heat deficit and the retention and transmission of liquid-water, both of which cause snow cover outflow to differ from snowmelt.

The model uses average temperature over a computation interval, daily in our case, to determine accumulation or melt. The snow water is tracked for each field. A field is defined in the SPUR hydrology component as an area of homogenous land use and/or soils, and it must be connected to a channel. These fields are basic units which SPUR uses to represent upland hydrologic processes on a watershed. In addition to data requirements, there are six major and six minor parameters for which values must be set for each field in order to use the model. A range of values and guidelines for selection are presented in the users' guide (Anderson 1973).

Snow accumulation is based on the average temperature during a precipitation event being less than or equal to PXTEMP, a temperature which delineates rain from snow. Since values of PXTEMP are set for each field, it is possible to consider elevation, aspect, or other differences in rain/snow occurrences.

Snowmelt processes are divided into rain-on-snow and nonrain melt categories, because energy transfer rates and seasonal variation in melt rates differ for the two processes. During rain-on-snow, melt is assumed to occur at the snow surface. It is also assumed that (1) incoming solar radiation is negligible because it is overcast, (2) incoming long wave radiation is equal to blackbody radiation at the temperature of the bottom of the clouds, which is close to air temperature, and (3) the wet bulb temperature is essentially the same as the air temperature. With these assumptions and the use of a standard atmosphere altitude-pressure relationship, the energy balance equation can be employed for computing melt during rain on snow (Anderson 1973).

During nonrain snowmelt periods a variety of meteorological conditions are possible which inhibit the use of energy relations as a basis for estimating snowmelt. Rather, an empirical air-temperature-based relationship was used, which contains only a melt factor, average air temperature, and a base temperature to delineate snow.

The model also contains provision for a small constant groundmelt component to be included. This melt is added to the snow cover outflow and to rain which falls on bare ground to obtain total rain plus melt.

One of the more distinct features of HYDRO-17 is the areal depletion curve (ADP), which relates water content of the snowpack to the percentage of the land surface covered. This feature increased the likelihood that the model could be used for a variety of snowpack conditions, including those encountered on rangelands, where drifts are more predominant. An additional curve was added to the relationship presented by Anderson (1973) to broaden the conditions covered. In addition, a procedure was developed to describe each curve and to interpolate between curves, thus enhancing user selection of an ADP curve to fit local conditions (Cooley et al. 1983).

[1] K. R. Cooley and E. P. Springer, hydrologists, and A. L. Huber, mathematician, USDA-ARS, Northwest Watershed Research Center, Boise, ID.

Validation of the Model

Two types of tests of HYDRO-17 have been conducted at the USDA-ARS Reynolds Creek experimental watershed in southwest Idaho. The first type of test consisted of comparing model-determined accumulation and melt values with measurements made at a standard snow course site. The model was first calibrated with the 1980 water year data. The simulated snowpack was compared to snow course survey data to compute the objective functions. The upper part of figure 1 depicts the fit obtained with the 1980 data. The correlation between the simulated and observed snow water equivalent (SWE) was 0.998.

Data for a 4-year test period, including the high and low years of record, were assembled to test the validity of the calibration coefficients. The test results are shown in the lower part of figure 1. The correlation between computed and observed snow water equivalent was 0.905 for this period (Cooley et al. 1983). In another study Huber (1983) compared HYDRO-17 to three other snow accumulation and melt models on snow course data and found its performance superior with the objective function used.

The second type of test involved using the SPUR model hydrology component on three small watersheds within the Reynolds Creek experimental watershed where snowmelt is important (Cooley et al. 1983, Springer et al. 1983). In this case calibration consisted of a comparison between simulated and observed runoff rather than snow accumulation and melt. Although it was not possible to separate the results into individual components, it appeared that timing of snow accumulation and melt in the individual fields was adequate. Results for the study period for the Murphy Creek watershed, including winter and spring snowmelt events, are shown in figure 2. The correlation coefficient between predicted and observed runoff amounts was 0.63 for Murphy Creek.

In general tests involving snow course, snow water equivalents, and small watershed runoff values indicate that timing of snow accumulation and melt simulated by HYDRO-17 produced reasonably good results. Some of the timing problems that do exist can be traced to the temperature-based snowmelt modeling routine. For example, the model worked very well for years 1971 and 1980 at the Reynolds Mountain snow course site but caused the snowpack to melt prematurely during 1970, 1972, and 1977 (figure 1).

These results suggest that under certain conditions, the ambient air temperature fails as an index of the physical processes that cause the snow to accumulate and melt. The inclusion of additional variables such as solar radiation, wind run, and vapor pressure should improve model results; however, these data are usually not available at the sites requiring simulation.

SUMMARY & CONCLUSIONS

The snow accumulation and melt model HYDRO-17 (Anderson 1973) was chosen for use in the ARS range model for SPUR, because of its minimal data requirements, program size, theoretical basis, parameter guidelines, previous use in many areas, and the reasonably accurate results obtained on tests at rangeland sites.

The model was tested against snow-water-equivalent measurements at a snow course site, and when combined with the hydrology portion of the SPUR model, against runoff from three subwatersheds of varying exposure, soils, elevation, and so forth, of the ARS Reynolds Creek experimental watershed near Boise, Idaho. In both of these types of tests adequate results were obtained with a minimum of calibration and parameter adjustment. The range of parameter values presented in the users' guide (Anderson 1973) proved adequate for both the point and basin tests at these locations.

Use of this model should provide better results over a wider range of snow accumulation and melt conditions than those obtained by simple constant times temperature models. However, as stated in the users' guide, there will still be situations where model results will not match actual snow conditions. In these cases only complete energy balance methods provide hope for better results, with the expense of considerably more detailed and comprehensive data sets.

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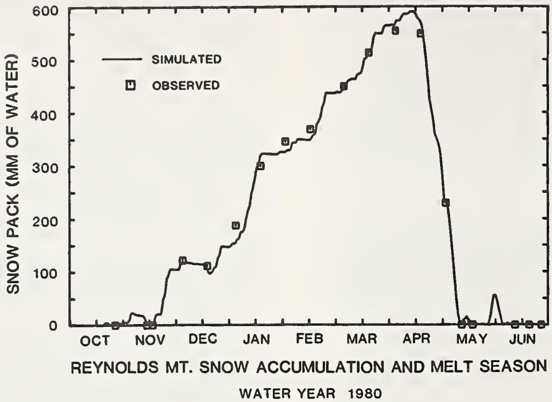

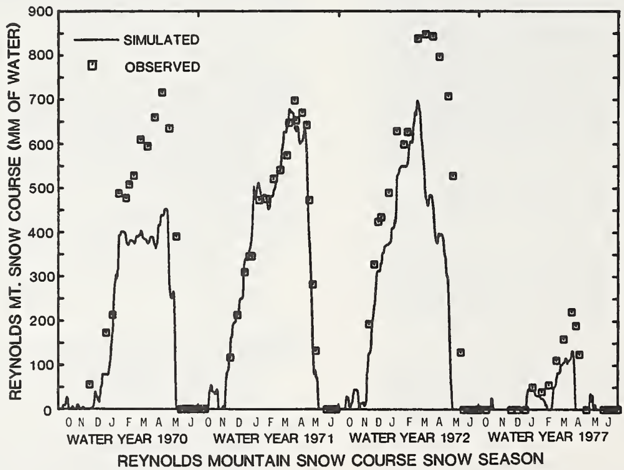

Figure 1.--Snow water equivalent at the Reynolds Mountain snow course for the calibration water year 1980 (above) and the 4 test years 1970, 1971, 1972, and 1977 (below) during the snow accumulation and ablation period. Simulated by the NWS HYDRO-17 model.

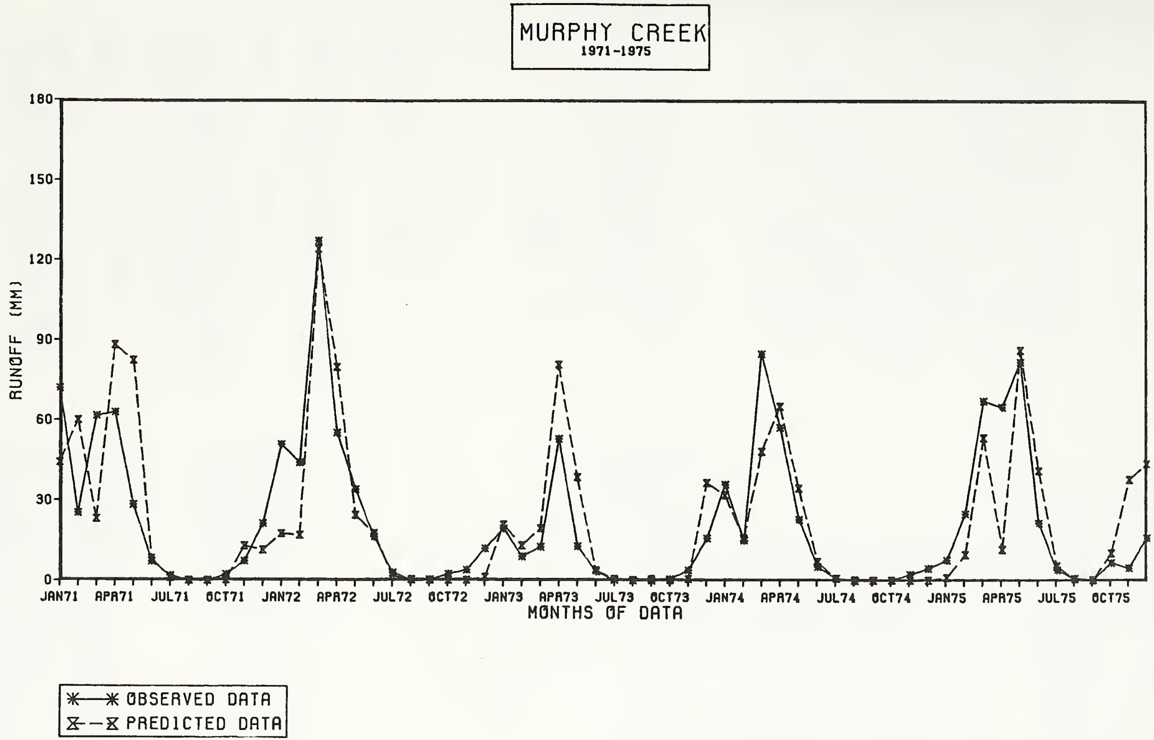

Figure 2.--Observed and model predicted monthly runoff for Murphy Creek [from Springer et al. (1983)].

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THE SNOWMELT-RUNOFF MODEL

Albert Rango[1]

INTRODUCTION

The Snowmelt-Runoff Model (SRM) was originally developed by Martinec (1975) to simulate and forecast daily flow in mountain basins where snowmelt is a major runoff factor. Originally run on small European basins, it was later applied to large international basins, thanks to the advent of satellite snow-cover data in the 1970's. Along with the use of the satellite data, modifications and improvements have been made to the model for use on large basins. Simulations are now possible for periods ranging from only a few days to an entire year, even though the model was originally operated only during snowmelt. The latest version is documented in user manual format (Martinec et al. 1983). Rather than describe SRM in a detailed fashion, which is available in the user manual, only the highlights will be discussed in this paper.

STRUCTURE

The flow diagram for SRM is shown in figure 1. Each day during the snowmelt season, the water produced from snowmelt and from rainfall is computed, superimposed on the calculated recession flow, and transformed into daily discharge from the basin according to equation 1.

$$Q_{n+1} = c_n[a_n(T_n + \Delta T_n)S_n + P_n]\,\frac{A \cdot 0.01}{86400}\,(1-k_{n+1}) + Q_n\,k_{n+1} \qquad (1)$$

where Q = average daily discharge in m^3/s

c = runoff coefficient expressing the losses as a ratio (runoff/precipitation)

a = degree-day factor (cm/°C·d) indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days (°C·d)

ΔT = the adjustment by temperature lapse rate necessary because of the altitude difference between the temperature station and the average hypsometric elevation of the basin or zone

S = ratio of the snow-covered area to the total area

P = precipitation contributing to runoff (cm). A preselected threshold temperature, T_{CRIT}, determines whether this contribution is rainfall and immediate.

A = area of the basin or zone (m^2)

$\frac{0.01}{86400}$ = conversion from $cm \cdot m^2/d$ to m^3/s

k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall:

$$k = \frac{Q_{m+1}}{Q_m}$$

(m, m+1 are the sequence of days during a true recession flow period)

n = sequence of days during the discharge computation period. Equation 1 is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 hours. As a result, the number of degree-days measured on the nth day corresponds to the discharge on the n+1 day. Different lag times will result in the proportioning of day n snowmelt between discharges occurring on days n, n+1, and possibly n+2.

If the elevation range of the basin exceeds 500 m, it is recommended to divide the basin into elevation zones of about 500 m each. For an elevation range of about 1500 m and three elevation zones A, B, and C, the model equation becomes

$$\begin{aligned} Q_{n+1} = \Big\{ & c_{An}\,[a_{An}(T_n + \Delta T_{An})S_{An} + P_{An}]\,\frac{A_A \cdot 0.01}{86400} + \\ & c_{Bn}\,[a_{Bn}(T_n + \Delta T_{Bn})S_{Bn} + P_{Bn}]\,\frac{A_B \cdot 0.01}{86400} + \\ & c_{Cn}\,[a_{Cn}(T_n + \Delta T_{Cn})S_{Cn} + P_{Cn}]\,\frac{A_C \cdot 0.01}{86400}\Big\}(1-k_{n+1}) \\ & + Q_n\,k_{n+1} \end{aligned} \qquad (2)$$

BASIN SIZE

The size of the basin to which SRM is applied has not been observed to be a limiting factor in the testing conducted thus far. Figure 2 illustrates the relative size of the basins tested. The model has been used on basins ranging from 2.65 km^2 to 4000 km^2, with no serious problems encountered.

DATA QUALITY

The model requires good daily air-temperature and precipitation data and periodical monitoring of snow-covered area in the given basin by satellites, aircraft, or visual observations. Long term historical data sets are not necessary (but helpful, if available) because little or no optimization (calibration) of the model parameters is necessary. The model can be run with as little as 1 to 2 years of record.

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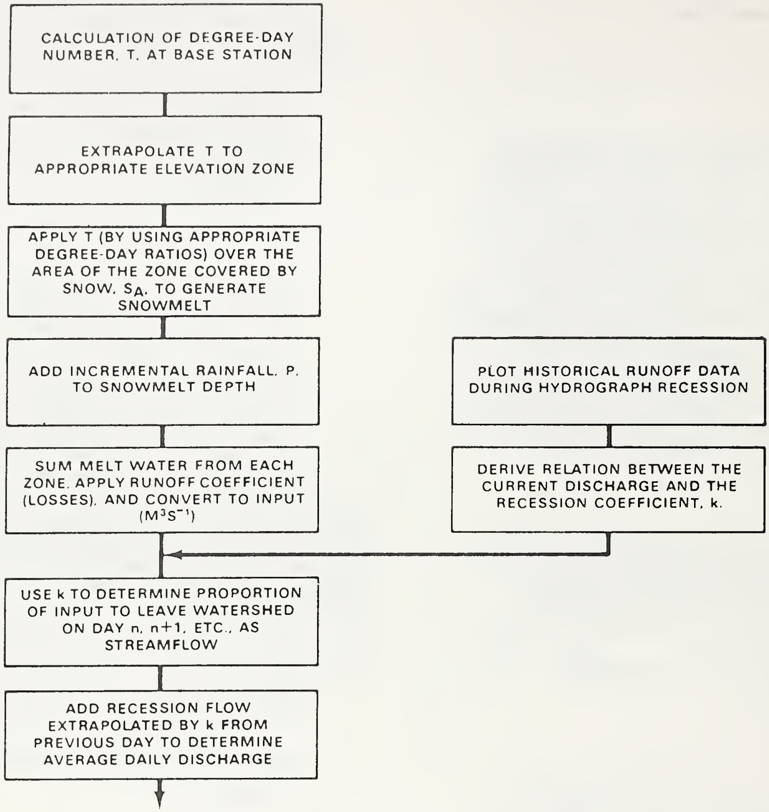

Figure 1.--Flow diagram for snowmelt-runoff model (SRM).

Daily discharge data from the basin are required to determine the recession coefficient and, otherwise, only to evaluate the accuracy of simulation. The discharge preceding the start of the snowmelt season (winter baseflow) must be known or estimated for initializing the model. Past continuous discharge records (hydrographs), if available, are useful to determine the time lag between the temperature and discharge cycles.

The optimum conditions for accurate simulation of runoff have been identified as follows: (1) temperature and precipitation are recorded at the mean elevation of the basin inside the basin boundaries (or at the zonal mean elevation for large basins); (2) snow cover is available reliably once per week to detect short-term variations in zonal areal extent; (3) several climatological stations are available for large basins, especially in areas with frequent summer precipitation events; and (4) several years of daily runoff records have been acquired for the determination of the recession coefficient. Decreases in accuracy will be expected as these optimum conditions are compromised. However, acceptable simulations will result even under the following minimum conditions: (1) temperature and precipitation data are observed outside the basin at a considerable horizontal and vertical distance, (2) snow-cover observations are only available two to three times during the snowmelt season, (3) climatological observations are not possible at multiple stations, and (4) no runoff records are available so that the recession coefficient must be estimated from the basin size.

RESULTS OF VALIDATION AND TESTING

One of the first indicators of how well a model simulates actual flow conditions is a comparison plot of computed and measured hydrographs.

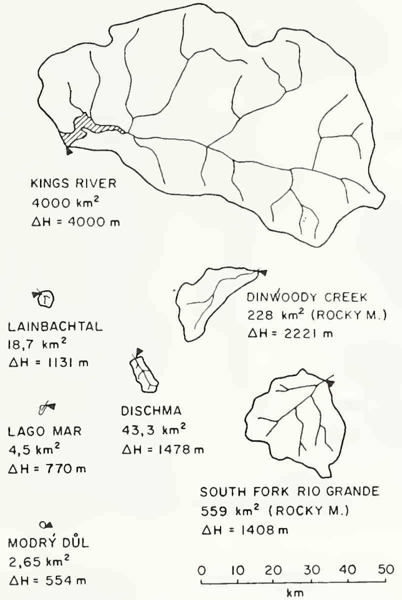

Figure 2.—Area and total basin relief (ΔH) of a selection of basins in which SRM has been applied.

Figure 3.—SRM simulated versus measured hydrograph for the Rio Grande near Del Norte, CO (3419 km^2) in 1973.

Table 1.—Basin characteristics and snowmelt-runoff model simulation results

Country	Basin	Size (km^2)	Elevation range (m)	Average goodness-of-fit statistics D_V(%)	NSR^2	n
Czechoslovakia	Modrý Důl	2.65	554	1.7	0.96	2
France	Durance	2170	3319	2.6	0.91	5
Japan	Okutadami	422	1564	5.4	0.83	1
Poland	Dunajec	700	1724	3.8	0.73	1
Spain	Lago Mar	4.5	770	N/A	N/A	N/A
Switzerland	Dischma	43.3	1478	2.4	0.86	10
United States	W-3	8.42	331	8.6	0.80	10
	Dinwoody Cr.	228	2221	2.8	0.85	2
	Bull Lake Cr.	484	2395	4.8	0.82	1
	South Fork	559	1408	1.8	0.89	7
	Conejos	730	1496	1.1	0.87	7
	Rio Grande	3419	1783	4.7	0.86	7
	Kings River	3999	4170	4.3	0.82	5
West Germany	Lainbachtal	18.7	1131	N/A	N/A	N/A

D_V = absolute percent volume difference; NSR^2 = Nash-Sutcliffe R^2 value;
n = number of years tested; N/A = not available.

Table 2.--SRM strengths and weaknesses

Strengths	Weaknesses
Daily input of only temperature, precipitation, and snow cover.	Snow-cover data not commonly observed.
No calibration necessary.	Satellite snow-cover data is sometimes difficult to obtain in a timely fashion.
Can be run on microcomputer or even hand calculator, if necessary.	Snow water equivalent data not yet formally incorporated in forecasting procedures.
Simple design where new algorithms could easily replace existing ones.	Does not have rigorous precipitation and evapotranspiration algorithms for operation during the non-snowmelt period of the year.
Operates effectively on basins in the size range 1.0-4000 km^2.	
User manual available for easy application to new basins.	
Elevation zone option available.	

Figure 3 illustrates this comparison for the Rio Grande basin (3419 km^2) in Colorado for the 1973 snowmelt season. Goodness-of-fit measures D_V (percentage volume difference for simulation period) and R^2 (Nash-Sutcliffe value analogous to coefficient of determination and measures the proportion of the variance of the recorded daily flows explained by the model) are plotted on the hydrograph for quantitative reference.

SRM has thus far been tested on a minimum of 14 basins, 9 of which are larger than 200 km^2 and required satellite snowcover input. The characteristics of these basins are listed in table 1 along with the corresponding goodness-of-fit statistics averaged over the number of years (n) tested. A general trend of decreasing goodness-of-fit values with decreasing quality of input data (usually with increasing basin size) can be perceived; however, many complexities are introduced by amount of snowmelt season precipitation, availability of snow-cover data, incomplete discharge diversion records, and varying quality of climatological data. From these results, it appears that SRM is applicable for runoff simulation on basins as large as 4000 km^2 with the following average accuracies: 96 percent for seasonal volume and 85 percent for daily flow.

STRENGTHS AND WEAKNESSES OF SRM

Table 2 presents a summary of the various advantages and disadvantages of SRM that may assist the user in deciding on its applicability for a particular situation.

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FROZEN SOIL MODELING

K. R. Cooley and J. F. Zuzel[1]

INTRODUCTION

In the Northwestern United States, frozen soil plays a major role in flooding and erosion. Both rainfall and rain on snow, with subsequent melting over frozen soils, result in rapid runoff causing severe erosion on hillsides and flooding of the lowlands. Johnson and McArthur (1973) analyzed winter floods in Idaho and the surrounding area for the 1955-72 period and found that of the 15 significant floods recorded, 13 involved rain on snow and 9 involved frozen soils. Yet, many of the hydrologic models presently being used to predict erosion and/or hydrologic response to management options do not contain provisions to adequately account for frozen soils so prevalent in the Northwest. This paper reviews some of the recent research concerning the physical processes of soil freezing and some of the frozen-soil model testing being conducted in the Northwest.

FROZEN SOIL RESEARCH

Lee and Molnau (1982) conducted infiltration studies on frozen soils using a rainfall simulator in a refrigerated chamber on frozen soil blocks (1.5-m square and 0.75-m deep). They also conducted field studies using a truck-mounted rainfall simulator and 1-m square plots. The laboratory tests included unfrozen samples, and samples with frost depths from 6 to 18 cm and soil moisture ranging from 15 to over 50 percent. The field tests were conducted with frost depths up to 38 cm and soil moisture near 30 percent.

Soil moisture contents were shown to be a major factor in determining infiltration capacity of a frozen soil. High soil moisture content (greater than 30 percent) resulted in low infiltration rates, while low-soil-moisture-content frozen soils could produce infiltration rates even greater than the unfrozen soil. Partial thawing of the frozen layer after 40 to 60 minutes of rain on the plots allowed infiltration to increase.

Cooley and Robertson (1983) conducted frozen soil and infiltration research on two field plots at the Reynolds Creek experimental watershed in southwestern Idaho. The plots consisted of a 1-m-square metal pan and a 1-m-square natural soil plot with a border. Runoff from both plots was recorded in addition to incoming precipitation, soil moisture, soil and air temperatures, snow depth, and water stored in the snowpack. Infiltration was calculated as the difference in runoff between the two plots. Water balance components for seven snow accumulation and melt periods are presented in table 1. Infiltration is seen to vary from 0 to 100 percent. Reasons for this great difference are better depicted in figure 1, which shows soil moisture content, soil frost depth, and snow cover for the 1982-83 winter period. The melting of snow on frozen soil early in the season, when soil moisture is relatively low, produces only slight amounts of runoff, or essentially 100 percent infiltration (see results for December 6 and December 21, 1982 in table 1). However, after soil moisture increases to some threshold level, almost all of the snowmelt occurs as runoff, or very low infiltration, (see results for January 8 and February 13, 1983 in table 1). These results are similar to those presented by Lee and Molnau, discussed previously, indicating the importance of soil moisture content at the time of soil freezing on the subsequent infiltration during rain or snowmelt events.

The effects of even small amounts of snow on the soil temperature at the 100-mm depth are also shown in figure 1. The 100-mm depth soil temperature fluctuates with changes in air temperature without a snow cover but remains almost constant during air temperature fluctuations once even a few centimeters of snow cover the surface.

TESTING OF FROZEN SOIL MODELS

Testing of Farnsworth Model

After a rather extensive literature review, Bullen (1982) selected the Farnsworth frost penetration model for testing against data from two watersheds in the intermountain West. However, he found that the large quantity of data required by this model would prohibit its practical use except at research sites. He therefore developed a modified version of the model which neglects evapotranspiration, and tested both models to determine their accuracy. His work indicated that the main factors effecting frost penetration are air temperature, thermal conductivity of the soil, soil moisture, and snow cover.

Overall, both models (Farnsworth and modified Farnsworth) produced reasonably accurate results over short periods of time and during years of shallow frost. Neither model simulated deep frost penetration accurately (frost below about 30 cm); however both simulated timing of frost entering and leaving the soil quite accurately. An example of simulated soil frost as computed by the models compared to observed soil frost is presented in figure 2 for the Nancy site in southern Idaho.

Testing of Modified Cary Model

The Cary model (1982), with modified inputs, has been tested using a data base from erosion monitoring sites located throughout the five northeastern Oregon counties in dryland wheat production. The model is designed to simulate or predict the presence or absence of frozen soil and was not designed for simulating frost depths.

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Table 1.--Water balance components for periods of snow accumulation and melt on small impervious and bare soil plots at Nancy watershed site

Period dates	Period (Days)	Cumulative precip. (mm)	Metal pan runoff (mm)	Evaporation (mm)	Evaporation (%)	Bare soil runoff (mm)	Infiltration (mm)	Infiltration (%)	Avg. wind run (km)
11/17/81-12/21/81	35	65.5	66.5	-	-	.3	66.2	99.6	10.8
12/22/81-2/17/82	59	79.4	Good snow event, but data lost due to equipment problems*						
2/18/82-3/12/82	23	11.9	11.9	-	-	0	11.9	100	8.4
11/20/82-12/6/82	17	23.9	25.4	-	-	.8	24.6	97	11.1
12/12/82-12/21/82	10	27.9	29.5	-	-	.8	28.7	97	13.4
12/22/82-1/8/83	18	17.3	15.5	1.8	10	19.8+	0	0	8.7
1/19/83-2/13/83	26	40.4	35.3	5.1	13	30.2	5.1	13	11.4

*Essentially all water in snow storage and precipitation did appear as runoff based on estimates of collection tank volumes.

+There may have been some snow left on the bare soil plot from the previous period.

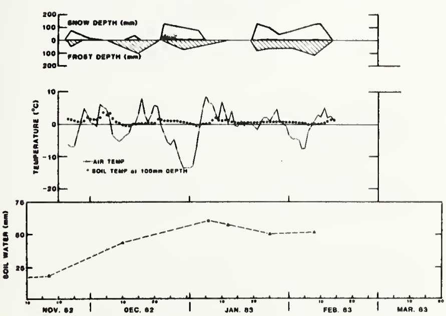

Figure 1.--Air temperature, 100 mm depth soil temperature, soil moisture in the top 230 mm layer, soil frost and snow cover at the Nancy watershed site for the winter of 1982-83.

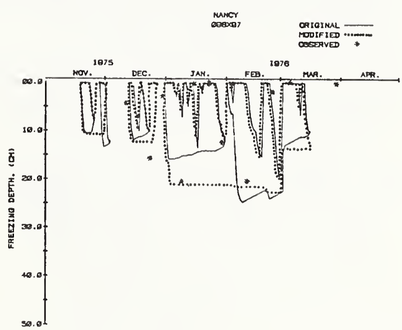

Figure 2.--Graphic comparison of observed and simulated frost penetration data for station 098X97 Nancy, 1975-78 winter (from Bullen 1982).

Initial results indicate that the model correctly simulates the presence or absence of frozen soil about 80 percent of the time. The model was also tested with a data set from the Reynolds Creek experimental watershed with satisfactory results.

SUMMARY & CONCLUSIONS

An accurate, easy to use, frost penetration model for use in more comprehensive hydrologic or management models is definitely needed. This model should use readily available data and be applicable under a variety of soil and surface conditions. Some of the existing models tested produced adequate results on timing of freezing and thawing of the soil but were not capable of accurately determining frost depth except for shallow frost conditions (less than 30 cm).

Results from numerous studies indicate that the main factors influencing soil frost and infiltration are (1) soil characteristics, texture, and so forth, (2) soil moisture content, and distribution within the soil profile at time of freezing, (3) surface conditions (snowcover, litter, vegetation, and so forth, and (4) temperature severity and length of freezing period.

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OVERVIEW OF SCS REQUIREMENTS

N. Miller*

To accomplish its mission, SCS, in cooperation with State and local governments and other Federal agencies, carries out programs of basic soil and water conservation, watershed protection, flood prevention, cooperative river-basin surveys and investigations, water supply forecasting, Great Plains conservation, water quality investigations, and resource conservation and development. All of these programs benefit from surface water modeling.

This overview describes major applications for surface water modeling in SCS programs, and some of the modeling requirements unmet. It also describes requirements relating to operational computer programs of the models.

SCS MODELS -- APPLICATIONS AND NEEDS

SCS currently requires surface water modeling for water supply forecasting, as described by Shafer at an earlier session, and for flood evaluation, farm water management, and water quality assessment, as described below.

1. Flood Evaluation. For many years, SCS has been evaluating floods and the economic damage caused by flooding. In evaluating floods, SCS is interested in flood peaks and hydrographs for these evaluations and uses an event model rather than a continuous simulation mode. Analysis of alternative sytems of flood control structures and land treatment measures is a fundamental part of hydrologic models used for project formulation.

   The SCS models most frequently used for flood evaluation are --

   a. A fundamental hydraulic model, WSP2, which computes water surface profiles for selected spatially varied discharges in natural channels and computes the area flooded in the stream reach representated. Needed for WSP2, for example, are improvements in the bridge and culvert subroutines.

   b. The companion hydrology model, TR-20, which develops subarea hydrographs of runoff from selected storms, then routes the floodwater through the appropriate stream reaches and reservoirs. It combines hydrographs of routed flows with other hydrographs in the proper time sequence to form a composite hydrograph of flow. TR-20 needs additional modeling for --

      (1) Runoff volume. An optional infiltration model is needed for use in lieu of runoff curve numbers (CN) when detailed precipitation data are available. We hope that this model can have several levels of complexity, depending on accuracy required and data available.

      Currently, Rawls, Brakensiek, and others are working on operational infiltration modes.

      (2) Unit hydrograph. SCS is using a dimensionless unit hydrograph which averages a large number of recorded hydrographs. Needed improvements include using watershed characteristics as a basis for varying the unit hydrograph shape. Certain kinds of areas, such as flatland areas, do not lend themselves to a linear response to runoff. A more accurate representation of flood hydrographs may be possible for flatland areas using another technique.

      (3) Time of concentration (T_c) evaluations. T_c methods should be more accurate than the velocity method currently used and better able to produce identical results for different users.

   c. The dams model, DAMS2, develops flood inflow hydrographs for reservoirs with various combinations of principal spillway design, floodwater volume, and surcharge storage capabilities. It also can calculate the volumes of fill material, concrete, and other supplies as well as costs. The planning engineer can then use this information for selecting the optimum combinations of dam size and cost for a site. An important need is the inclusion of a flood routing routine, which may simulate unsteady flow, to model the effects of dam breaching. SCS's Hydrology & Hydraulics (H&H) model, currently under development, will include such a routine.

   d. The economics model, ECON2, takes the output on physical damage caused by floodwater and computes the average annual monetary damages in each evaluation reach. Needed are criteria for selecting storm type, duration, and frequency, that is, criteria that provide the most appropriate basis for evaluating flood damage to agricultural land.

2. Farm water management. SCS is using surface water modeling to study drainage, irrigation, and crop responses to water movement and availability. Needed are models of water yield and continuous simulation models.

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3. Water quality assessment. SCS needs models of surface and subsurface water flow to help determine how pesticides, nutrients, sediment, and other pollutants move through a hydrologic system.

In order to meet some of our needs at SCS, we are working on a hydrology and hydraulics (H&H) model. Our main emphasis is on the reach routing subroutine. We are evaluating reach routing methods ranging from coefficient methods to variations in the solution of the complete St. Venant equations to obtain a more accurate representation of a flood wave as it moves through a complex channel system.

SCS needs improved descriptions of the physical processes (mathematical models) in some of the subroutines. They also require continuous simulation models to answer many of the questions relating to the long-term effects of conservation practices on water quality and quantity. The CREAMS model, for example, uses a continuous period of several years to give a more accurate prediction of the effectiveness of resource management systems than evaluation on an individual storm basis. CREAMS, however, does need expansion beyond field size analysis.

REQUIREMENTS FOR OPERATIONAL COMPUTER MODELS

SCS has several crucial operational requirements relating to computerization of the models:

1. The computer program must be user friendly. That is, it must be easy to understand and to operate. SCS personnel will be primarily responsible for developing the user friendliness of an operational computer program and, therefore, must clearly identify the user.

2. The computer program must work in ungauged areas. Most SCS work is in watersheds where stream gauge data are not available. Therefore, the model(s) should not depend on calibration.

3. Input data must be readily available. Because SCS analyzes many projects each year, it has to depend upon readily available data. For the most part, we cannot take the time to make site-specific studies that require instrumentation or special measurements, such as installing an infiltrometer ring to determine the infiltration characteristics of the soil; therefore, we must rely on available information such as standard soil survey data and range site data. This is one reason the CN procedure is so popular. If we find from research that certain additional data are needed, perhaps we can include these in our regular data gathering and processing activities.

4. The model must be robust. A robust model or program is one that is stable under a wide range of conditions. A stable model generates answers that make sense. It does not blow up, that is, does not give nonsense answers, such as negative values where only positive values are possible; and it does not need extensive manipulation. A robust model is also user friendly. An example of a nonrobust model is the National Weather Service's DAMBRK model, which can be run only by experienced hydraulic engineers. When it "blows up," only experienced hydraulic engineers have the knowledge to manipulate the input data to get the model to run and give results they're looking form.

5. The program must be efficient. SCS personnel run programs such as TR-20, DAMS2, and WSP2 thousands of times annually. These programs must be efficient to keep costs down.

6. The model must satisfy several levels of accuracy. Requirements of accuracy for design of a farm pond in an agricultural area are very different from the requirements for a multipurpose million dollar structure located near a populated area.

SUMMARY

SCS needs surface water models that are efficient, user friendly, and stable to solve problems in water supply forecasting, flood evaluation, farm water management, and water quality assessment. To meet these program needs, SCS seeks to coordinate its research needs with the efforts of ARS's many expert research scientists working on hydrologic models and to support, in any way it can, ARS assistance.

SURFACE WATER MODELING: AN ARS OVERVIEW

Donn G. DeCoursey[1]

The natural resources modeling symposium has been divided into two parts. One part was used to present general overviews of large scale modeling and related activities of ARS. The second part consists of four concurrent sessions (Chemical and Biological Processes; Soil, Water, Plant, and Economic Relations; Hydrology; and Erosion and Sedimentation Processes) within which the state of the art and research priorities are assessed in detail. Both ARS and SCS overviews of the state of the art will be presented in these sessions. This is an overview of surface water modeling for hydrology.

RECENT MODEL DEVELOPMENT

Presentations and discussion at this symposium show that model development over the past 10 to 15 years has progressed rapidly from the statistically based USLE, empirical infiltration equations, and the unit hydrograph era to a much more comprehensive approach for evaluating surface water problems. Although most of the models have remnants of the older technology imbedded in them, there is a tendency to develop causal models based on physical processes. Klemes (1982) describes the advantages of causal model development as (1) the ability to derive the behavior of a hydrologic process, for a given state of the system, from dynamic mechanisms without recourse to calibration by empirical fitting. Thus, these models can be used to predict hydrologic response under conditions that did not exist during process-recorded history, (2) the inherent ability to assess the effects of environmental changes on water resources, (3) the potential to point out ways to efficient shortcuts and thereby to better empirical models, (4) the systematizing research to provide a rational methodology for hydrologic model use. Thus it should be apparent why most model development in ARS has moved in the direction of causal models.

However, the development of causal models is not without its problems. Such models require large volumes of data for development and use, and they often need extensive basic research programs to develop and test their concepts. In spite of these disadvantages, the following presentation will emphasize the need for further development of causal models.

WHAT ARE THE MOST PRESSING NEEDS IN CONSERVATION AND MANAGEMENT OF OUR NATURAL RESOURCES?

Use of water resources worldwide continues to grow, diminishing excess supplies; thus, it becomes increasingly important that we manage existing supplies with greatest possible efficiency. Until recently, the time scale and areal extent of hydrologic projects have been such that our knowledge and forecasting ability have been able to provide adequate guidance. However, the effects of human activity are now a more dominant part of the hydrologic cycle; both quality and quantity are being affected by it and affecting it (Matalas et al. 1982).

The National Research Council (1982) identifies several long-term and large-scale water management problems. These are (1) ground-water contamination due to toxic and nuclear-waste disposal; (2) effects of nonpoint sources of pollution on stream systems; (3) impacts of change in both flow and water quality on the aquatic ecosystem; (4) the frequency, duration, and impacts of drought, including long-term trends toward desertification; (5) long-term hydrologic budgets for assessing the adequacy of regional or national water resources; (6) global geochemical cycles such as the fate of nitrogen and sulfur (for example, acid rain); and (7) protection of engineered system (for example, nuclear power plants) against hydrologic extremes. If we superimpose on this list, those issues related to our dwindling land resource base, we have a comprehensive description of the problems we in ARS face.

If we address more specifically the current issues and problems of interest to SCS and other action agencies, we can develop a similar list of research priorities. In the last 2 years, statements of need have been prepared by Larson et al. (1981), The Soil Conservation Service (1983), The National Association of Conservation Districts (1981), and the USDA-Resources Conservation Act (1981) document. Research priorities for the Nation (Larson et al. 1981) provide a list of six priorities within which all of the above needs can be shown. These six priorities are (not necessarily in priority order) (1) sustaining soil productivity, (2) developing conservation technology, (3) managing water in stressed environments, (4) protecting water quality, (5) improving and implementing conservation policy, and (6) assessing soil and water resources. The research needs as identified by the above groups using these six priorities as focal points are presented below.

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Priority Soil and Water Research Needs

1. Sustaining Soil Productivity

   - improve understanding of soil erosion/productivity relationship
   - develop improved methods of conservation or reduced tillage practices

2. Developing Conservation Technology

   - reduce flood damage in upstream areas
   - improve water conservation
   - address community related conservation problems
   - develop a better understanding of gully development prior to prevention and control

3. Managing Water in Stressed Environments

   - develop crop production systems for areas with limited water supply
   - obtain more information on rainfall and runoff characteristics that affect erosion in the southern and western states

4. Protecting Water Quality (and Environmental Conditions)
   - protect and improve water quality
   - improve fish and wildlife habitat
   - develop a better understanding of land use, crop production, and conservation as related to nonpoint sources of water pollution

5. Improving and Implementing Conservation Policy

   - improve water supply management and allocations
   - improve understanding of socio-economic factors affecting adoption of conservation practices

6. Assessing Soil and Water Resources

   - improve management of organic wastes
   - develop better methods of assessing concentrated flow erosion
   - determine the net economic benefits of conservation practices
   - evaluate effects of new grazing systems
   - improve use of USLE on rangeland
   - improve spillway design
   - develop better estimates of wind erosion and damage assessment
   - evaluate impact of conservation management systems on energy requirements for food and fibre production

HOW SHOULD WE RESPOND TO THESE NEEDS?

The research priorities described in the list and the seven water management problems involve large investments and the health and well-being of large segments of our population. Thus, they set the stage for serious discussion of the analytical procedures needed to solve them. They also emphasize problems and differences in approaches currently in use. Three examples are

1. The difference in viewpoint and practice between empirical and causal models. Empirical models, frequently used by action agencies to solve today's problems, require continuous updating and fitting to onsite data. It is hazardous to extrapolate beyond the range of data used in the development or to transfer from one place to another. Causal models, based on physical principles can in theory incorporate the effects of change in the environment. In principle, they are also transferable in space and time.

2. The difference between models for prediction and understanding. Generally prediction is directed toward meeting immediate needs, and may use whatever means are practical. Understanding is oriented toward causality and improved ability to explain the response of processes in both space and time.

3. The solution of most problems is focused at local spatial and temporal scales with little thought given to the larger hydrologic scale of which the local problems are a part. We must begin working toward an understanding and description of the total hydrologic cycle.

Solution of high priority problems requires continued development of causal models that improve our understanding of the real world. These models will be similar to those described in the first part of this symposium. They will require more investigation of fundamental processes than we usually have done in the past. However, practical application of these models usually will require a blending of empirical and causal models. The research-oriented models required to describe these problems in complete detail will be too complex and require too much data to be used in most practical situations. Thus, the causal or research models must be used as a foundation for developing applications models. The problems outlined above involve complex systems. Thus, their solution will require stable models that are based on an understanding of the real world situation and can predict the response of some system perturbation accurately. Frequently, USDA scientists/engineers are questioned regarding downstream effects of land use and management alternatives; thus both temporal and spatial scales of these problems must be considered in a more realistic way.

HYDROLOGIC IMPROVEMENTS NEEDED

Many of the problems identified above go considerably beyond classical hydrology. In fact, most of the high-priority research is not centered in the area of hydrology, but is

expressed in terms of problems. Hydrology, and the need to improve our science, enters the picture because water is the transport medium that provides the inputs and receives the outputs of processes of primarily concern to other sciences, that is, plant growth, soil erosion, nutrient, and chemical movement.

A review of the priority needs from a hydrologic perspective shows that they can be grouped into several classes of problems or technical objectives requiring fundamental hydrologic research or expertise.

1. Improvement in understanding and predicting infiltration and the movement of water in the soil and vadose zone as influenced by vegetation, tillage, surface sealing, biological activity, erosion, and other factors.

2. Improvement in understanding and predicting the movement of soluble materials (nutrients, salts, and other chemicals) and how that movement is influenced by tillage, crusting, erosion, biological activity and other factors that change soil structure and roughness.

3. Improvement in understanding and predicting the mechanisms of erosion and transport of sediments on both a local and macroscopic scale. On a local scale, this will require more information on raindrop impacts and erosion, the stochastic structure of turbulence and shear mechanisms, and their interaction with bed surfaces and sediment particles. On the macroscopic scale, it will require more data on the mechanics of bed flow, armoring, cross channel or lateral distributions of aggregation and degradation; the effects of channel-bank vegetation and conditions on channel erosion, sediment movement and flow resistance; the mechanics of transporting sediment mixtures and their effect on channel hydraulics and erosion, meandering, head cutting, mass wasting, and removal of mass-wasted material.

4. Improvement in understanding and predicting the hydraulic effects of mixing and dispersion on the lateral and downstream movement of soluble and adsorbed chemicals. Turbulence and transport mechanisms in the interstices of the bed material also influence the interchange or mixing of adsorbed and soluble materials and dissolved oxygen.

5. Development of procedures to simulate the effects of land use and management on the quality and quantity of water at some distance downstream, that is, the development of basin-scale water quality models. Methods to extrapolate across mixed soils, land use, and topographic conditions to produce a realistic response at realistic costs are not available.

6. Improvement in understanding and predicting the scale and effects of temporal and spatial variability of precipitation and other meteorological data. Methods of generating meteorological data for any location are needed. Widescale availability of daily data (for example, precipitation) preclude making and accepting models other than those capable of working in daily time increments. Yet significant improvement in predictive capability will require use of meteorological data over shorter time intervals.

7. Improvement in understanding and responding to the spatial and temporal variability of parameters describing soils, erosion rates, permeability, vegetative response, and evapotranspiration.

8. Development of fundamental expressions for wind erosion on various soils and plant cover complexes.

9. Improvement in understanding and predicting the interaction of biological factors and the movement of water, nutrients and other chemicals.
10. Improvement in the use of probability distributions of input variables and parameter values to add the dimension of risk to predictions of hydrologic responses.

This list of hydrologic research needs emphasizes the importance of approaching the problem solution from a complete systems point of view. That does not mean that fundamental research must be regimented into a system, but it does not mean that overriding models of complete process systems must be used to guide the fundamental research and data collection programs. By approaching the solution to these problems from a fundamental perspective, resulting data and models can be applied to many more problems, that is, gravity and sprinkler irrigation, agricultural as well as range and forested lands, and wetlands as well as lakes or ponds.

APPLICATIONS OF MODELS

The solution to problems identified in this brief overview emphasizes the strengthening of fundamental research coincident with development of causal models of the physical processes under investigation. Application of these models to real world problems often, usually requires that the models be simplified where possible to reduce input data requirements and yet maintain stability and robustness for new situations. Model application requires close working relations between the user agency and the researcher. The user knows what data bases are available, the skill of the technician using the model, and the best form for input and output. By working together as a team, the researcher and user can adapt the model to meet the user's needs. Even though the simplified model may include empirical components, it will have been developed from a

causal foundation, thus the structure of the model will be sound. The model should then have the capability of realistically responding to the user's demands with minimal calibration. A description of such a coordinated effort between ARS and SCS recently was prepared by DeCoursey, et al. (1983).[2]

SUMMARY

A review of research needs by the National Research Council identified several long-term and large-scale water management problems: groundwater contamination, nonpoint sources of pollution, aquatic ecosystem deterioration, long-term effects of drought, long-term water budgets for national water resources, global geochemical effects, and protection of engineered systems. Superimposed on this national perspective are problems of direct concern to ARS and SCS. Statements of research needs expressed by SCS, the National Association of Conservation Districts, the USDA-Resources Conservation Act document, and people at the workshop on Research Priorities for the Nation were summarized under the six priorities listed in the latter report. These priorities are: (1) sustaining soil productivity, (2) developing conservation technology, (3) managing water in stressed environments, (4) protecting water quality, (5) improving and implementing conservation policy, and (6) assessing soil and water resources. The research needs identified by these different groups include a wide range of research objectives in hydrology that must be addressed before the problems can be solved. Solution to these problems will require coordinated research programs for data collection and model development. The models must be causal in structure and able to describe in a physical way how the different systems respond to perturbations. Applications of these models will require coordinated development between ARS and action agencies such as SCS.

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SIMULATING SURFACE RUNOFF IN CREAMS2

R. E. Smith[1]

DESCRIBING THE FIELD SHAPE AND SLOPE CHARACTERISTICS

To simulate hydrology of a catchment, the actual topographic shape must be interpreted in terms of hydrologically representative set of planes and receiving channels. The mean flow path slope pattern may be described in some detail, as illustrated below, whereas a natural catchment map shape must be interpreted to a variable extent into geometrically more simple units.

The general interpretation of an elementary catchment is illustrated in figure 1. The transformation or mapping of the actual catchment shape into the geometrical hydrological equivalent must preserve the following features:

1. Catchment area,
2. Mean surface (or overland) flow path length,
3. Net slope of the mean flow path,
4. Concentrated (or channel) flow path length.

Figure 1 shows the method for accomplishing such representation in one example. Points on the natural topography at the top of the figure have been mapped to hydrologically similar points on the interpreted catchment below. Area, mean flow path lengths, and net slopes have been preserved, and the detailed slope profile along the mean flow path may be retained as well. Note that convergence of the overland flow is also preserved by matching the width of flow at the catchment divide with a similar dimension in the geometrical representation. The shallow flow surface of the field is here called a plane, but it is never necessarily a truly plane surface, and the longitudinal changes in slope may be described in some detail. Local slope may be described at every major change in slope or slope trend. Slope pattern is thus described by an array of data pairs, consisting of a local slope and the distance from the top of the field or catchment divide to the given point.

CREAMS2 allows the user to construct the total field hydraulic geometry with multiples of a simple unit. As indicated above, the basic unit may be either a one-sided (MULP=1) or a two-sided (MULP=2) element (such as in fig. 1). This feature allows the description of more complex field shapes, such as fields with divided flow and, particularly, terrace systems, as illustrated below. The number of units aggregated is termed NUN.

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CREAMS2 also recognizes that tillage and resultant furrows can significantly affect the actual hydrologic geometry of the area. Thus, hydrologic geometry data is read for both the natural, untilled (KL=1) and the furrowed (KL=2) flow paths for a given field. For simulation of untilled or natural catchments, only the first (KL=1) case need be read.

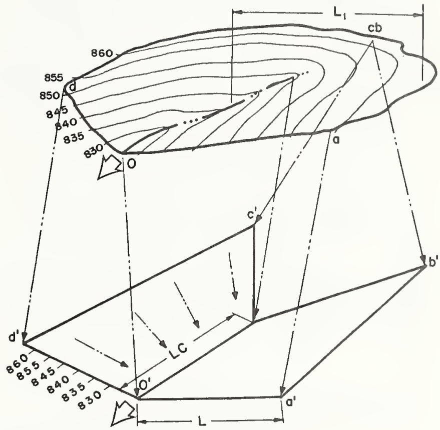

Figure 1.--Schematic illustration of topological mapping from actual catchment to geometrically simplified catchment with conservation of principle hydrologic dimensions.

Figures 2 and 3 show an example of the two geometries that describe flow paths for one field. In figure 2, flow follows the natural shape, flowing perpendicular to the contours, and thus converging towards the outlet, here pictured as a small impoundment pond.

If the same field is tilled as shown in figure 3, furrows will cause runoff to flow along the left to right furrow channels. Convergence cannot occur in furrowed (KL=2) conditions without overtopping overcoming the furrow control. In the furrowed condition here, the total flow path is lengthened and the slope profile is flattened and changed, but the total elevation change from top to bottom should be preserved. In the symbols used in figures 2 and 3,

$$(XLP_1)(SPL_1) + (XLC_1)(SC_1) = (XLP_2)(SPL_2) + (XLC_2)(SC_2)$$

where SPL is net plane slope and SC is net channel slope.

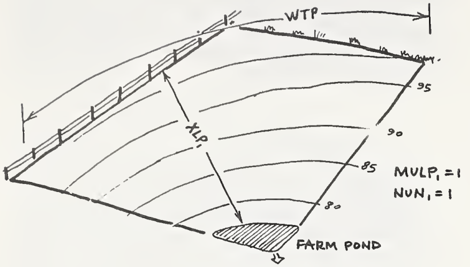

Figure 2.--Basic hydrologic dimensions for a simple converging untilled rectangular field. There is no channel in this case.

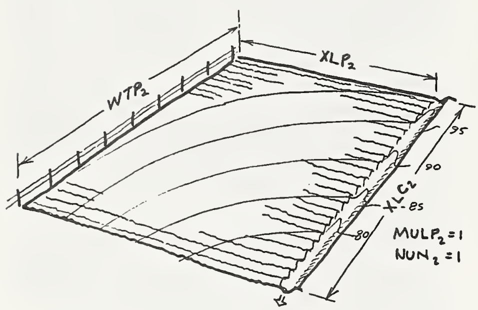

Figure 3.--Basic hydrologic dimensions for the field of figure 2 when it is tilled as shown, directing flow to a lateral receiving channel.

DAILY RAINFALL DATA RUNOFF OPTIONS

As in CREAMS (USDA 1980) runoff from daily rainfall data is estimated with a modified SCS curve number method. Because this method is lumped in time and space, there is no separation of infiltration and runoff as physical processes. Options 2 and 3, however, attempt to apply assumptions to the curve number (CN) runoff estimate that allow use of some of CREAMS2 topographic information about the field in estimation of transport processes on the surface. The four options available are summarized in the description of CREAMS2 given elsewhere in this proceedings.

Option 1 Hydrology

The curve number estimate of runoff is supplemented by a stochastic estimate of runoff peak discharge, as in CREAMS and EPIC (Williams et al. 1982). Erosion amount is estimated using MUSLE, utilizing CREAMS2 information on surface and crop conditions in the erosion estimate. Particle size enrichment ratio is estimated by an empirical function of erosion loss, runoff peak, and total runoff.

Option 2 Hydrology

This option will be very nearly like the existing erosion methodology in CREAMS and will not be elaborated on here.

Option 3 Hydrology

Based on the CN estimate of runoff and the stochastic estimate of runoff peak, this option constructs a synthetic triangular rainfall excess pattern and routes it across the field topography. This procedure allows consideration of spatial variability in many of the important transport processes--notably erosion. It should be considered a synthetically distributed model. The features of distributed flow simulation used are summarized in option 4, below.

BREAKPOINT (TIME AND SPACE DISTRIBUTED) HYDROLOGIC MODEL

Use of data on time distribution of rainfall intensity allows simulation of fully time and space distributed surface water dynamics. This allows greater physical realism in simulation of transport and patterns of erosion loss.

Infiltration

Infiltration parameters are taken directly from the hydraulic soil properties used in soil water transport simulation, so not only are no additional parameters necessary, but also the two processes are physically linked as they should be.*

The infiltration model is that of Smith and Parlange (1978),

$$f = \frac{K_e \exp(F/G)}{\exp(F/G)-1} \tag{1}$$

*In CREAMS (Option 1) one problem occasionally encountered was that a user could input incongruous parameters for soil and surface properties, and the soil routing would be asked to treat inappropriate amounts of infiltrated water.

in which f = infiltration capacity, mm/min,

K_e = effective net saturated hydraulic conductivity in the wetted zone, mm/min,

F = net infiltrated water, mm, and

$G = G(\theta_i)$ = integrated measure of capillary potential in the wetted zone, mm.

The philosophy of the infiltration method is discussed in a recent paper by Smith (1983) and will not be treated in detail here. Equation 1 suffices under proper applications to both preponded and postponded conditions, for as long as rainfall rate $r \geq K_e$. After for a long hiatus with $r < K_e$, initial water content, θ_i, is estimated as

$$\theta_i = \theta(r)$$

using r in the $\theta(K)$ relation. The value of G is a function of both soil properties and θ_i. It can be obtained as an analytic function of the Brooks-Corey (1964) soil parameters.

All management operations can change the physical and hydraulic conditions of the soil surface, and CREAMS2 interprets these effects in terms of changes in K_e and soil porosity for infiltration calculations. Rainfall alters the surface layer by forming crust conditions after cultivation on exposed soil, and these changes are also simulated in determining K_e. Figure 4 outlines the method used. It is not theoretically complete, insofar as appropriate changes in G should also be calculated. Research is underway to produce an analytic method for bulk $G(\theta_i)$ changes from crust formations. The treatment of crusting in CREAMS2 is felt to be conservative in extent, and it should add significantly to the simulation quality in comparison to omission of specific crust considerations.

Surface Flow Routing

Infiltration and surface runoff processes are interdependent, since infiltration at a point will continue past the end of rainfall as long as a depth of surface water is available for satisfying f. Only option 4 treats this interaction. Both options 3 and 4 treat the hydrodynamics of rainfall-excess-generated runoff across the surface. The kinematic wave equations are solved with an implicit four-point method for each time step, after rainfall excess rate is calculated for that step. Erosion and sediment transport, if required, are also calculated before the next time step is considered. A routing subroutine has been devised that can be used for either surface (furrow or "plane") or channel hydraulic computations. This subroutine calls upon another subroutine which computes the necessary hydraulic geometry at each location along the low path. Vectors of flow unit areas and velocities are retained for subsequent use in erosion and

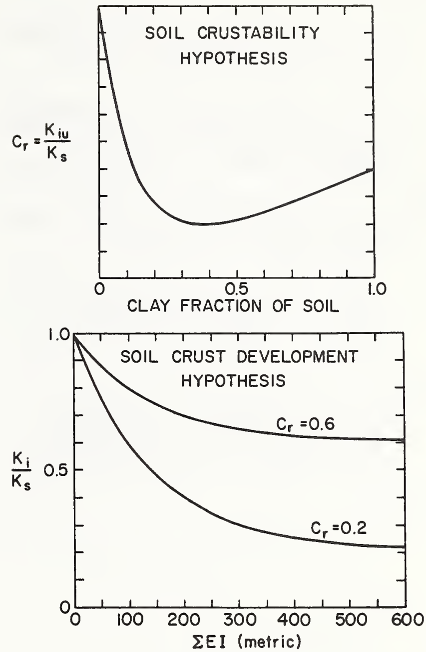

Figure 4.--Graphical presentation of the soil crusting assumptions in CREAMS2. The upper figure indicates the relation between ultimate saturated hydraulic conductivity, K_{iu}, of the crust and its clay content. The lower figure shows the reduction in K_i as a function of accumulated rainfall energy, EI.

deposition calculations. Temperature of the runoff water is assumed, for want of specific information, to be near that of the daily minimum air temperature.

The time steps for infiltration, plane and channel runoff, and sediment transport are identical, and the computations are made sequentially in the above order. The time step is some subdivision of the given breakpoint rainfall time increment. Step size is chosen automatically on the basis of the rate of change in the rainfall excess rate, with smaller steps appropriate to more rapidly changing rates.

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EVALUATION OF GREEN AND AMPT INFILTRATION PARAMETER ESTIMATES

D. L. Brakensiek, W. J. Rawls, and C. A. Onstad[1]

INTRODUCTION

We will report on comparing Green and Ampt estimates made by using our previously published procedures with a number of measured infiltration data sets (Rawls and Brakensiek 1983, Brakensiek and Rawls 1983). The data sets were compiled from reported testing by Mannering (1967), sites 1, North Central Regional Committee 40 (1979), sites 2, Rawls et al. (1976), sites 3, Onstad (1983), sites 4, and Devaurs (1983), sites 5. Tables 1, 2, and 3 summarize the scope of these data for the test sites.

The comparisons utilize infiltration rates and amounts and, when available, time to initiation of surface runoff. It is assumed that the predicted quantities are validated if they fall within a standard deviation of observed values. The Green and Ampt equation tests utilize the two layer model described in Brakensiek and Rawls (1983).

For those tests where a surface crust was forming or was in place, the model simulates a surface layer and subcrust layer. With no crust, a single layer soil profile is simulated.

Our procedure for estimating Green and Ampt parameters from charts in the publication by Rawls and Brakensiek (1983) is as follows:

1. Calculate total porosity from the measured or estimated bulk density.

2. Select the appropriate porosity chart (matching or as close as possible) corresponding to the known or assumed percent sand and clay. We now assume that the bulk density includes the effects of organic matter.

3. From the appropriate charts, read the Green and Ampt parameters of effective porosity, ϕ_e, wetting front capillary pressure, ψ_f, and the saturated conductivity, K_s.

Antecedent soil water is subtracted from ϕ_e to give available porosity. We use K_s for the K parameter. This differs from our earlier work where we assumed that K_s would be divided by two (Brakensiek et al. 1983). There is an indication that for the coarser textured soils, K_s should be divided by two.

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TEST SUMMARIES

Data Sets 1, 2, and 3

From data sets 1, 2, and 3a, a total of 95 soils were utilized. Most of these soils were in a seedbed or fallow condition. The dry run test results are used in our comparisons. Tests were grouped as silt loams (51 soils), loams (10), silty clays (12), and loamy sands and sands (22). From these data sets, a subset of grass plots was selected (19 soils) and tested. Table 4 summarizes the mean statistics calculated for the final infiltration rates. In sandy soils where a restricting layer was identified from the profile description, a multilayer model was used in lieu of our two-layer Green and Ampt model. Obviously, layer changes in hydraulic properties must be modeled if water penetrates to those layers.

The predicted mean final rates are within one standard deviation interval of the mean calculated from observed final rates. In general the final rate for sandy soils is overestimated. However, the silt loams, which cover many agricultural soils, exhibit a closer correspondence between measured and predicted. The pooled statistics from all 95 tests indicate our model and predicted parameters yield a larger variability (40 percent greater). However, the statistics for the sandy soils indicate a dependence of infiltration variability upon the mean. Their variance greater inflates the overall sample variance.

The grass plots were either silt loams or silty clays. A procedure for adjusting soil bulk densities for the grass plots was as follows: For soils with greater than 30 percent clay, the porosity was increased by 30 percent; for soils with greater than 60 percent sand, porosity was not increased; for other clay and sand amounts, porosity was increased by 20 percent. This is our attempt to account for surface and surface connected porosity due to roots and mulch.

Site 4

One group of the plots at site 4 was chisel plowed and the other group was moldboard plowed. Table 5a and b present the comparison of the dry run and wet run for these two tillages. Mean values for total infiltration and final rate (dry run duration - 2 h and wet run duration - 1 h) are consistently underestimated. However, the absolute error is much less than 15 percent. Our crust model is overestimating the time of ponding for the dry runs. However, a sensitivity analysis indicates that time to ponding is very sensitive to crust parameters, whereas final rates and amounts are not. Thus, time to ponding is reduced by assuming a thicker crust.

A second set of tests available from Minnesota studies on four soils was composed of three plots, with a dry run and a wet run on each. The plots were plowed and disked. Runoff was measured with a tipping bucket type gauge. These data exhibited a characteristic of tilled or rough surfaces which

Table 1.--Summary of rainfall simulator factors and plot conditions at test sites

Sites	Application rate	Duration of test	Site runs	Antecedent soil treatment	Plot size	Soil surface
1	6.35 cm/h	1 h	Dry & wet	Fallow	12'x35'	Screen/ unprotected
2	Ranged from 3 to 6 in/h	50-90 min	Dry & wet	Seedbed clipped corn	3.81'x 3.81'	Natural
3	Ranged from 4-6 in/h	90-300 min	Dry & wet	Fallow	3.81'x 3.81'	Natural or clipped
4	Ranged from 6.35-11.7 cm/h	60-120 min	Dry & wet	Tilled	3'x5'	Exposed
5	Ranged from 6.35-11.7 cm/h	30 min	Dry & wet	Tilled & natural	2'x2'	Exposed

Table 2.--Summary of collected data at sites

Sites	Soil description	Bulk density	Soil water	Infiltration rates	Infiltration totals	Time to ponding or runoff
1	Texture	Yes	No	Final	Final	Runoff
2	Texture & particle sizes	Yes	Yes	Mean rates	No	Runoff
3	Texture	Yes	Yes	Yes	Yes	Runoff
4	Texture & particle sizes	Yes	Yes	Yes	Yes	Ponding
5	Texture & particle sizes	Yes	Yes	Yes	Yes	Runoff

Table 3.--Additional available data for Minnesota tests (sites 4)

Surface cover	Surface roughness	Bulk density	Other
Measured percent	Measured random roughness before and after each test	Measured before and after each test	Surface exposed to to natural consolidation

Table 4.--Predicted and measured statistics for final infiltration rates

Set	N	Mean in/h	Standard deviation in/h	Minimum value in/h	Maximum value in/h	STD error of mean in/h
			Soil type = silt loams			
Observed	51	1.43	0.57	0.25	3.05	0.08
Predicted	51	1.39	0.49	0.26	2.80	0.07
			Soil type = loams			
Observed	10	1.57	0.61	0.80	2.50	0.19
Predicted	10	1.60	0.41	1.02	2.48	0.13
			Soil type = silt clays			
Observed	12	1.42	0.63	0.51	2.54	0.18
Predicted	12	0.93	0.40	0.29	1.63	0.12
Observed	22	4.30	2.38	1.21	10.00	0.51
Predicted	22	4.74	3.99	0.13	12.85	0.85
			Soil type = all except sands			
Observed	73	1.45	0.58	0.25	3.05	0.07
Predicted	73	1.35	0.50	0.26	2.80	0.06
			Soil type = all			
Observed	95	2.11	1.73	0.25	10.00	0.18
Predicted	95	2.13	2.41	0.13	12.85	0.25
			Grass			
Observed	20	2.55	1.05	0.64	4.95	0.23
Predicted	19	2.14	0.65	1.02	3.12	0.15

Table 5a.--Infiltration parameters for chisel plowed Barnes loam sites in Minnesota

Plot/ tillage	TP[1] Meas.	TP[1] Pred.	Total F[2] Meas.	Total F[2] Pred.	Rate f[3] Meas.	Rate f[3] Pred.
	min		cm		cm/h	
1 - Chisel						
Dry	10	29	9.3	8.9	3.5	3.1
Wet	2	.9	2.4	3.7	2.2	3.2
2 - Chisel						
Dry	8.5	31	10.4	9.0	4.6	3.1
Wet	1.2	.9	4.4	3.7	4.3	3.2
3 - Chisel						
Dry	3.5	22	8.2	8.5	4.4	3.1
Wet	?	1	3.9	3.8	3.7	3.2
4 - Chisel						
Dry	7	16	8.6	8.2	4.3	3.1
Wet	?	.8	4.0	3.7	3.7	3.1
Mean			6.4	6.2	3.8	3.1

[1]Time to ponding.

[2]Total infiltration at the final infiltration rate.

[3]Final infiltration rate.

Table 5b.--Infiltration parameters for moldboard plowed Barnes loam sites in Minnesota

Plot/ tillage	TP Meas.	TP Pred.	Total F Meas.	Total F Pred.	Rate f Meas.	Rate f Pred.
	min		cm		cm/h	
1 - Plow						
Dry	15	32	9.9	8.9	3.5	3.1
Wet	2	.7	2.2	3.6	.35	3.1
2 - Plow						
Dry	18	29	12.2	8.6	5.9	3.0
Wet	2	.8	4.4	3.7	3.4	3.2
3 - Plow						
Dry	4	23	9.5	8.3	3.5	3.1
Wet	?	.9	3.5	3.8	2.7	3.2
4 - Plow						
Dry	8	20	10.1	8.6	4.6	3.2
Wet	?	.8	4.2	3.7	3.97	3.1
Mean			7.0	6.2	3.5	3.1

may confound infiltration calculations. The assumption that infiltration is application rate minus runoff rate is complicated by rapid changes and/or spikes in the runoff rates. This is probably due to rapid changes in surface storages on tilled surfaces. The high application rate for the dry runs appeared to smooth the surface prior to the wet run. Random roughness measurements indicated a much smoother surface for wet runs.

Table 6 presents the summary of this set of tests. Wet and dry runs are pooled for each soil, that is, six plots for each.

The Green and Ampt parameters estimated from available soils information for Sverdrup sandy loam soils estimated no runoff. That is, the estimated saturated conductivity exceeded the application rate. The SCS Soils 5 file indicates that Sverdrup sandy soil grades toward a fine sandy loam and, thus, would have a much smaller conductivity. However, from available data this could not be quantified.

Assuming that the pooled wet and dry run data represents a valid sample population, the mean and variability of time to ponding, final infiltration rates, and infiltration amounts, then our predictions are mostly within one standard deviation of measured values.

Site 5

Large plots (3.05 m x 10.67 m) at three sites on the Reynolds Creek watershed were tilled as part of an evaluation study of USLE factors for rangeland soils. Within each of these plots, 10 small infiltration tests were made. Wet run results are presented in table 7, along with the calculated statistics from measured infiltration data from the 10 sites within each plot. Soil properties were measured from a bulk sample taken for large plots. The measured properties were bulk density, organic matter, percent sand, silt and clay, and antecedent soil water. An application rate of 12.7 cm/h was used for each test. Runoff amounts were calculated at selected time increments during a 30-minute run at each site.

Table 7 indicates that our estimated parameters and Green and Ampt model estimate mean infiltration rates are nearly within one standard deviation of measured mean rates. Again, the comparison of predicted time of ponding is with initiation of measurable runoff, which is generally greater than time of ponding.

CONCLUSIONS

Our parameter estimations in the Green and Ampt model generally predict infiltration rates and amounts approximately within one standard deviation of the mean calculated from measured quantities. Time to ponding is less accurately predicted; however, the crust thickness is very sensitive to the time of ponding. Predicted saturated conductivity of very sandy soils tends to be high. However, if the Green and Ampt parameter K is taken as one-half of K_s, then reasonable modeling is possible.

Modifications of soil water properties of soils by agronomic practices are not well documented by research. Modifications of soil porosity by a grass cover, as used in these tests, are tentative. Spatial and temporal variability of soil properties is well recognized; however, the characterization and incorporation of this variability into infiltration and runoff modeling requires much more research.

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Table 6.--Infiltration parameters for Minnesota soil sites (Mean + SD)

Soil	Time to pond Meas.	Time to pond Pred.	Rate at 1 h Meas.	Rate at 1 h Pred.	Amount at 1 h Meas.	Amount at 1 h Pred.
	min		cm/h		cm	
Barnes loam	(3.6±2.8)	7.1	(4.3±3.2)	3.2	(5.8±3.3)	4.9
Forman clay loam	(6.1±5.5)	5.1	(6.5±3.2)	2.6	(7.5±3.4)	4.3
Egan clay loam	(4.4±3.0)	3.5	(3.0±1.7)	2.0	(5.6±3.3)	3.5
Sverdrup sandy loam	(5.4±4.3)	---	(5.4±3.5)	---	(6.8±3.8)	---

Table 7.--Comparisons of infiltration statistics for three soils on the Reynolds Creek Watershed

Site	Time to ponding Meas.[1] ±SD	Time to ponding Pred.	Infiltration at ponding Meas. ±SD	Infiltration at ponding Pred.	Rate @ 1500 s Meas. ±SD	Rate @ 1500 s Pred.	Infiltration @ 1500 s Meas. ±SD	Infiltration @ 1500 s Pred.
	s		cm		cm/h		cm	
Flats sandy loam	109 ±40	58	0.39 ±.14	0.20	1.38 ±.64	1.94	1.12 ±.31	1.54
Nancy, loam	132 ±39	28	0.46 ±.14	0.10	2.29 ±.66	1.32	1.54 ±.59	1.11
Lower Sheep, loam	78 ±20	97	0.27 ±.07	0.34	2.32 ±.44	2.39	1.53 ±.19	1.89

[1]Initial runoff.

A GREEN AMPT TYPE MODEL FOR INFILTRATION THROUGH A SURFACE SEAL

L. R. Ahuja and J. D. Ross[1]

BACKGROUND

A Green-Ampt type method recently presented and validated by the senior author for infiltration through a stable, surface-seal or crust is developed further to describe infiltration through a transient seal as well. The model properly incorporates the use of transient unsaturated hydraulic conductivities, capillary drive terms, and soil water contents below the seal. Calculation of infiltration before seal formation begins for a certain rainfall intensity and before runoff begins is included in the development. Based on the literature, hydraulic resistance of the transient seal is taken as an exponential function of the cumulative rainfall kinetic energy. The Green-Ampt type equation is solved for cumulative infiltration volume and time in small preset intervals of infiltration flux and related transient soil water contents and suctions below the seal by using known unsaturated hydraulic conductivity, suction-water content, and seal resistance characteristics of a soil. An iterative scheme is used to incorporate transient changes in seal resistance.

Studies with the model provided several useful insights on the effects of different rainfall intensities, soil hydraulic properties, and seal formation characteristics on infiltration and soil-water suction changes below the seal. Rainfall intensity influenced runoff initiation time and infiltration rates for early to intermediate times only. Cumulative infiltration-time curves for different intensities were close together, and could be approximated as one curve. A simple power-form equation could adequately describe this curve.

THEORY AND RESULTS FOR A STABLE SEAL

Development of surface seal due to rainfall impact will cause the soil below the seal to remain unsaturated, but with the soil water content and suction changing with time (Edwards and Larson 1969; Ahuja 1973). For infiltration through a stable seal or crust, the following Greem-Ampt type equation was developed (Ahuja, 1983) to apply at any given time:

$$v_o = K(\theta_o)\frac{[H_c(h_o,h_i) + Sq/(\theta_o-\theta_i)]}{Sq/\theta_o-\theta_i)} \qquad (1)$$

where: v_o, infiltration rate into the soil;

θ_o, transient volumetric soil water content at the crust-soil interface,

θ_i, constant initial value;

h_o, transient soil-water pressure head (negative of suction) at the crust-soil interface, a function of θ_o;

h_i, constant initial pressure head;

$K(\theta_o)$, unsaturated hydraulic conductivity corresponding to θ_o or h_o;

q, cumulative infiltration, as depth of water;

S, a profile shape factor; and

$H_c(h_o,h_i)$, capillary drive, defined as

$$H_c = \int_{h_i}^{h_o} [K(h)/K(h_o)]dh \qquad (2)$$

It should be noted that K, H_c, and θ_o in equation (1) are not constants but time dependent variables. The factor S is supposed to approximately correct for the deviations, due to the effect of wetted profile shape, in the values of gravity term in the numerator and the resistance term in the deonminator of equation (1) from the square-wave estimate $q/(\theta_o-\theta_i)$. In general, the value of S may vary with time.

Equation (1) was used in conjunction with the following boundary condition of flux through the stable saturated crust:

$$V_o = \frac{-h_o + L_c}{r} \qquad (3)$$

where L_c is the thickness of crust and r its constant hydraulic resistance. With known K(h) and θ (h) functions of soil, equations (1) and (3) were used to obtain Sq as a function of v_o. For any chosen value of S, the $q(v_o)$ was integrated piecewise to obtain q(t). With S set equal to 1.0, the q(t) values computed for Yolo light clay soil were only slighly higher than the q(t) values obtained by a finite-difference numerical solution of the Richards Equation, subject to the boundary condition of equation (3). The results are presented in figure 1 for two values of crust resistance r. The solid curves are the numerical solutions. The dots are the Green-Ampt method just described, with S=1. Maximum difference in the two sets of q(t) occurring at a large time (10^4 min) was less than 10 percent (Ahuja 1983). Figure 1 also shows results obtained by a piecewise application of the conventional Green-Ampt method, which looks good. However, use of the conventional Green-Ampt method, assuming a constant, steady-state, water content at the crust-soil interface, results in large discrepancies. A comparison of q(t) computed by using S=1 in equation (1) with experimental data for another soil showed generally good agreement between the two methods, within experimental

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errors in data points and estimation of soil hydraulic parameters. Therefore, the S in equation (1) may be taken somewhere between 1.0 and 1.20 without causing a serious error.

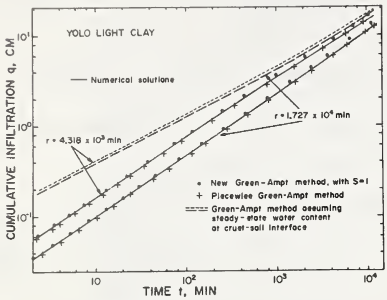

Figure 1.--Cumulative infiltration q(t), calculated by three different methods based on the Green-Ampt approach, compared with numerical solution results for two crust resistances of Yolo soil.

MODEL RESULTS FOR A TRANSIENT SEAL

For a transient surface seal, equation (1) was solved simulataneously with equation

$$V_o = \frac{-h_o + L_c}{r(t)} \qquad (4)$$

for each time. The r(t) is the transient hydraulic resistance of the seal. Based on literature, the r(t) was taken as

$$r(t) = r_f + (r_o - r_f)e^{-aIE(t-t_r)} \qquad (5)$$

Here r_f is the final steady resistance of the seal and r_o is the resistance at runoff initiation time t_r. The I is the rainfall intensity, E is the kinetic energy per unit depth of rainfall and a is a constant.

For a solution of equations (1), (4) and (5), a piecewise iterative approach was used that is described in detail elsewhere (Ahuja and Ross 1983). The calculations of infiltration through a transient seal was first done for Yolo light clay soil. Values of the final steady seal resistance, r_f, chosen for this soil were 5 and 20 times the hydraulic resistance of saturated Yolo soil layer of 0.5-cm thickness.

Two other soils with hydraulic conductivity 10 and 100 times greater than that of the Yolo soil were generated by scaling based on the similar media concept of Miller and Miller (1956). We will refer to Yolo soil as soil-1 and the other two as soil-2 and soil-3, respectively. The r_f values used for these generated soils were adjusted by the above factors.

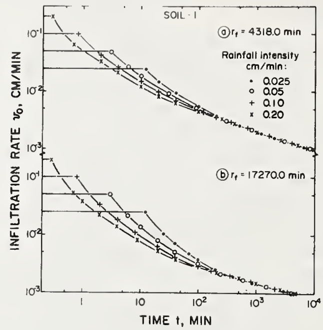

Figure 2.--Infiltration rate through a transient seal as a function of time in soil-1, computed by the new Green-Ampt method for different rainfall intensities with the final steady seal resistance (r_f) equal to (a) 4318.0 min, and (b) 17270.0 min.

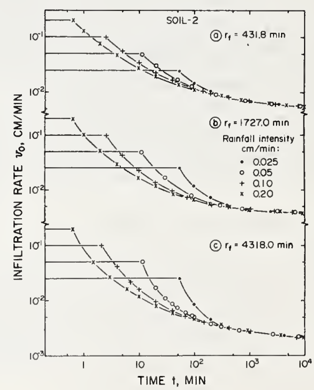

Figure 3.--Infiltration rate through a transient seal as a function of time in soil-2 for different rainfall intensities, with r_f equal to (a) 431.8 min, (b) 1727.0 min, and (c) 4318.0 min.

Infiltration rates, v_o, as a function of time from the four different rainfall intensities in soil-1 are presented in figure 2. As expected, the time up to which all rainfall infiltrates into the soil (runoff initiation time) increases as the rainfall intensity decreases. After this

time, the infiltration rate decreases with time, more rapidly in figure 2b, where the seal resistance increases more rapidly with time to approach a higher final value (r_f) and a smaller final steady infiltration rate. After 3 to 4 hours, the infiltration rates at any fixed time are about the same for all four rainfall intensities for a given r_f value.

The above trends in infiltration rates are also observed in the data for soil-2 (figure 3) and soil-3. However, as the soil's hydraulic conductivity increased, the runoff initiation time increased, the infiltration rates were higher throughout, and the steady rate was attained more quickly.

Cumulative amounts of infiltration with time for different rainfall intensities and r_f values in soil-2 are plotted in figure 4, a to c. For the smallest r_f value (figure 4a), the computed values for all rainfall intensities merge closely together as one curve. This curve can be approximated for the most part as a straight line on the log-log plot, described by a power-form equation. As r_f increases (figure 4b, c), cumulative infiltration curves for different intensities are more separated during early to intermediate times, when the cumulative infiltration is greater at lower intensities. However, the deviations may be tolerable for practical applications. Results for soil-1 and soil-3 were similar to those shown in figure 4. Adequate representation of the cumulative infiltration for different rainfall intensities in a given soil by a single power-form curve is an interesting and useful finding.

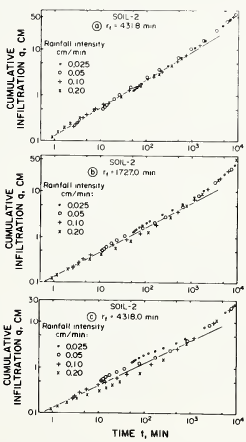

Figure 4.--Cumulative infiltration as a function of time for different rainfall intensities in soil-2, with seal r_f equal to (a) 431.8 min, (b) 1727.0 min, and (c) 4318.0 min.

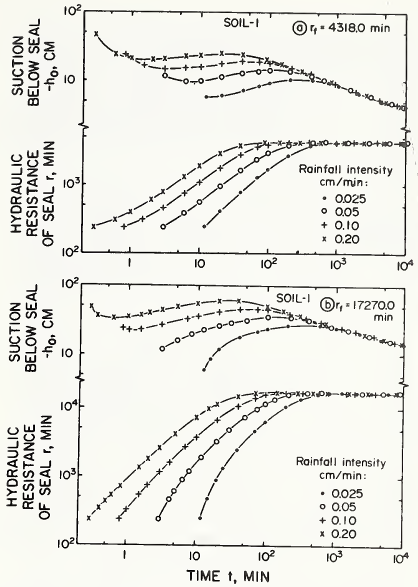

Figure 5.--Changes in soil-water suction below the transient seal and in hydraulic resistance of the seal with time for soil-1, with r_f equal to (a) 4318.0 min, and (b) 17270.0 min.

Changes in soil-water suction below the transient seal (at the seal-soil interface) and in hydraulic resistance of seal (r) with time for two r_f cases of soil-1 are shown in figure 5, a and b. During early to intermediate stages the suctions are higher for higher rainfall intensities, but at large times all intensities result in the same transient values of suction. This pattern of suction changes is related to the changes in seal resistance with time; the seal resistance is higher for higher rainfall intensities in early to intermediate stages but approaches the same constant value for all intensities at large times (for a given r_f value). Suction curves for each intensity have a local maximum value at a time when the corresponding seal resistance curve shows a transition from steep rise with time to a constant value. For the two or three highest intensities, the suctions initially decrease with time, then increase, and finally decrease with time again to slowly approach, presumably, the final steady value. The initial decrease in suction with time is probably a result of fast development of surface seal at higher rainfall intensities. The suctions at any given time are higher with a higher value of the final seal resistance r_f. The maximum values at intermediate times are as high as 60 cm H_2O.

The magnitude of transient suctions decreased with the increase in hydraulic conductivity of soil, but increased with increases in rainfall intensity and hydraulic resistance of the seal. In soil-2, the highest intermediate maximum suction valve was between 6 and 23 cm, depending upon the r_f value; and in soil-3, between only 1.95 and 3.65 cm.

Thus, our results presented above show the significant effects of soil type, rainfall intensity, and seal resistance changes on the transient suctions below the seal--effects that must be considered when modeling infiltration.

CONCLUSIONS AND APPLICATIONS

The Green-Ampt type model for infiltration through a surface seal presented in this paper has a theoretical basis, with reasonable approximations. It is more realistic than earlier versions of the Green-Ampt equations adopted for describing infiltration through a seal, because the model properly incorporates the use of unsaturated and transient hydraulic conductivities, soil water contents, and the capillary drive terms. The model is much simpler than the finite-difference solutions of the flow problem. For large-scale hydrologic applications, the simple Green-Ampt equation is now widely used for infiltration in the absence of a surface-seal crust. The new model presented here extends its use and should phase in well with existing models.

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SURFACE SEALING AND INFILTRATION - A SYNOPSIS

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INTRODUCTION

Surface sealing is generally understood to mean the process of reducing water entry into the soil profile due to structural changes of the soil surface by raindrop impact and/or slaking action. Depending on the degree of sealing, the impact of seal formation on the infiltration/runoff process may be quite substantial. Upon drying, the surface seal becomes a crust in which soil particles have become reoriented, further consolidated, and often mutually bonded.

The objective of this article is to review infiltration relative to surface sealing effects, to summarize research needs, and to indicate possible means of improving infiltration predictions under sealing conditions.

SEAL FORMATION AND MORPHOLOGY

Morphological descriptions of rainfall induced crusts have been given by Duley (1939), McIntyre (1958), Tackett and Pearson (1965), Evans and Buol (1968), Falayi and Bouma (1975), Chen et al. (1980), and others. These descriptions were usually based on microscopic examination of thin sections. McIntyre (1958) observed a 0.1-mm thick "skin seal" over the entire soil surface. This seal was attributed to compaction effects by impacting raindrops. However, he also recognized other morphological effects induced by rainfall, such as aggregate dispersion, the washing-in of dispersed material into soil pores, and settling of suspended material following the cessation of rainfall. Tackett and Pearson (1965) measured substantial differences in the strength and permeability of crusts formed on material of the Ap- and B_2-horizon of unaltered Hartsell fine sandy loam (Hapludalf) on one hand and, following the removal of binding agents, of the reconstituted horizons or their separates on the other hand. The permeability characteristics of crusts formed in the reconstituted materials were appreciably smaller than those of the original soils. Crust thicknesses were observed to be 1- to 3-mm thick. Evans and Buol (1968) presented evidence of differences in crust development under natural field conditions among different soils and among different management practices on the same soil. Similarly, Falayi and Bouma (1975) observed appreciably lower crust conductances in different tillage systems of sodded soil than on soil in continuous corn rotation. Also, crusts formed on top of clods had significantly larger conductances than crust from between-clod areas. Furthermore, conductances of crusts formed under short-term high energy experimental rainfall were not significantly different from those formed under natural conditions during a 4-month period of intermittent low-energy rainfall. Recent scanning electron microscope observations on crusts by Chen et al. (1980) corroborated the Falayi and Bouma (1975) findings of differences in crust characteristics in depressional areas and those developed on elevated bulk soil (structural crust). The depositional crust was mainly formed by translocation of fine particles resulting in a thin skin of about 0.1 mm thickness at the surface. On the other hand, structural crusts form in three stages: (1) an initial stage with uniform particle distribution, (2) a middle stage with a surface consisting of coarse particles stripped from fine ones, and (3) a final stage consisting of a thin seal skin of about 0.1 mm thickness.

Studies on surface sealing and crusting have erroneously given the impression of uniformity in thickness and morphology of surface crusts over the entire surface. In reality, surface crust may vary substantially between different locations on a surface.

INFILTRATION PREDICTIONS THROUGH CRUSTS

The effect of crusts on infiltration can be very substantial. Various studies have attempted to quantify infiltration into crusted soils. These efforts included analytical as well as numerical techniques under a variety of simplifying assumptions. The simplest case is that of steady infiltration (Hillel and Gardner, 1969) into a crust-topped soil. The next level of complexity is transient infiltration into a crust-topped soil (Hillel and Gardner, 1970; Ahuja, 1974; Ahuja, 1983), and the most complex case concerns infiltration into soil with transient seal development (Farrell and Larson, 1972). All these approaches are based on the Green-Ampt model in which infiltration is described by Darcy's law for the piston-shaped wetted part of the soil profile. Furthermore, the crust is assumed to be instantaneously saturated. Other simplifications included the absence of a hydraulic head at the soil surface and a homogeneous, infinitely deep, soil profile beneath the crust.

In the steady infiltration approach by Hillel and Gardner (1969), the flux across the crust was equated with the flux in the wetter part of the profile, yielding the following expressions for the infiltration rate:

For desaturated subcrust:

$$q = a^{1/(n+1)}/R_c^{-n/(n+1)} \qquad (1)$$

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For saturated subcrust:

$$\frac{q}{K_s} = \left[\frac{h_a}{K_s R_c}\right]^{n/(n+1)} \qquad (2)$$

where q is the infiltration rate, K_s is the saturated hydraulic conductivity, h_a is the air entry suction of the subcrust soil, R_c is the crust impedance (= crust thickness/crust conductivity), and a and n are the subcrust soil parameters as given in the conductivity-pressure head relationship $K = a|h|^{-n}$. In this model of steady infiltration, the hydraulic properties of both the crust and subcrust soil affect infiltration.

In the case of transient flow, Hillel and Gardner (1970) reduced the driving force for infiltration into the subcrust soil by the head loss through the crust. By equating the flux through the crust to the flux through the wetted soil profile ($\Theta = \Theta_e$ for $L_c < Z < L$), the solution to Darcy's law

$$dI/dt = (H_F + L_F)/(R_c + R_u) \qquad (3)$$

for I = 0 at t = 0 is given by the relationship

$$L_F - (H_F - K_u R_c) \ln \left(\frac{H_F + L_F}{H_F}\right) = K_u t/\Delta\Theta \qquad (4)$$

where L_F is the wetting front depth, $\Delta\Theta = \Theta_e - \Theta_i$ is the difference between the initial (Θ_i) and (Θ_e) soil water content in the subcrust soil, R_c is the crust impedance, H_F is the pressure potential at the wetting front, R_u is the impedance through the wetted part of the subcrust soil, K_u is the hydraulic conductivity of the subcrust soil, and t is the time. The underlying assumption of the acquired relationship (4) is the validity of a constant soil water content at the crust/soil interface and in the wetted part of the subcrust profile. Hillel and Gardner (1969, 1970) concluded that infiltration into a crust-topped profile can be approximated by water entry into the subcrust soil at a nearly constant pressure head.

Ahuja (1974) recognized the potential error source in computing infiltration for the case of a constant soil water content at the soil crust/soil boundary. In testing the Hillel and Gardner (1970) relations with numerical solution data for Yolo light clay (Xerochrept), he obtained fair predictions of infiltration into crust-topped soils having small crust resistances ($R_c < 4.3 \times 10^3$ min), but arrived at appreciable errors for crusts with large resistances ($R_c > 1.7 \times 10^4$ min). To include the effect of the transient soil-water content at the crust-soil boundary on infiltration, Ahuja (1974) modified the Hillel and Gardner (1970) approach by a piecewise application of their relations (3) and (4). In this approach, the soil water content at the crust-soil boundary was increased by equal increments at successive time steps and the values for the pressure head and a constant were computed from the numerical solution-generated values of I and dI/dt. Close agreement was obtained with the numerical solution for both small and large resistances. It is probable that this computational scheme represents a refinement in the application of the Green-Ampt model, but the physical significance of the constant, except as a fitting parameter, is not clear. Ahuja (1974) also used a continuously variable boundary water content at the crust-soil interface. By using the Green-Ampt equation of the form

$$dI/dt = K(\Theta) + S.D(\Theta).(\Theta-\Theta_i)^2/q \qquad (5)$$

subject to the condition

$$dI/dt = \left(h(\Theta) + L_c\right)/R_c \qquad (6)$$

the following integral equation was obtained

$$\frac{t}{R_c{}^2 S} = \int_{\Theta_t}^{\Theta} \frac{1}{h(\Theta) + L_c} \cdot \left[\frac{D(\Theta) \cdot (\Theta-\Theta_i)^2}{h(\Theta) + L_c - R_c K(\Theta)}\right] d\Theta \qquad (7)$$

where L_c is the crust thickness, $D(\Theta)$ is the soil water diffusivity function, S is a constant, Θ_i is the initial soil water content, $K(\Theta)$ is the hydraulic conductivity function, $h(\Theta)$ is the soil water pressure head, and Θ is the time-dependent soil water content on the boundary. This expression gave very good agreement for both resistances with the numerical solution during early stages of infiltration. However, the physical meaning of S is not apparent, except in combination with $D(\Theta)$ as an effective diffusivity term. More recently, Ahuja (1983) used an approximate Green-Ampt type formulation for predicting infiltration through a crust-topped soil in which the wetting front pressure head HF was replaced by a time-dependent capillary drive term $H_c = \int_{H_i}^{H_o} K(h)dh$ at the crust-soil interface analogous to that proposed by Bouwer (1964) and discussed by Morel-Seytoux and Khanji (1974). This relationship, which also includes a profile shape correction factor, S, is

$$v_o = K(H_o) \cdot \frac{\left[H_c + Sq/(\Theta_o - \Theta_i)\right]}{Sq/(\Theta_o - \Theta_i)} \qquad (8)$$

where $H_o(t)$ is the time dependent soil water pressure head at the crust-soil surface, H_i is the initial pressure head, and $\Theta_o = \Theta(H_o)$ is the transient soil water content at the crust-soil interface. The profile shape factor is constant during early to intermediate times and becomes unity at very large times.

Infiltration through a transient crust, using the Green-Ampt infiltration model, was described

by Farrell and Larson (1972). Solutions of Darcy's law, when expressed as

$$\frac{dz}{dt} = \frac{\Delta\Theta}{K_u}\left[\frac{L_F + R_c(t)K_u}{H_F + L_F}\right] \quad (9)$$

were obtained for several relationships $R_c(t)$, including $R_c = \alpha t^{1/2}$, $R_c = \alpha t$, and $R_c = C_o - C_1 \exp(-\alpha t)$ for both the absence ($L_F \ll H_F$) and the presence of the gravitational component. C_o, C_1 and α are constants. Of these relationships, the exponential decay function is, from a physical standpoint, the most realistic model. A similar model was proposed for the hydraulic conductivity of surface seal by Moore et al. (1980) and used in numerical simulations by Moore (1981). The solutions, given in terms of the incomplete gamma function if the gravitational component was included and in terms of the error function if only the pressure head term was considered, were not supported by experimental results.

In short, various infiltration equations have been proposed for steady and transient infiltration into crust-topped soil and infiltration into soils with transient seal formation. All these relationships were derived for a Green-Ampt type infiltration model.

INFILTRATION MODELS OF SURFACE SEALING

Several studies have attempted to model seal development and its impact on infiltration. Seginer and Morin (1970) derived a theoretical model of crust formation based on the following assumptions: (1) crust formation is caused by impacting raindrops; (2) crust formation of the impact area is final following the impact of a raindrop; (3) the rate of change of the soil surface converted into a crusted area is proportional to the fraction of the soil surface that has not been affected by raindrops, (4) infiltration into a crusting soil is based on Darcy's law, in which the impedence term is composed of parallel arranged impedances of the crusted and noncrusted part of the surface area connected in series with an uniform noncrust impedance for the subcrust soil. The model yields a Horton-type infiltration equation in which the exponential factor reflects the effect of soil and rain characteristics. This model was experimentally tested by Morin and Benjamin (1977) on bare soils and was found to confirm the theoretically derived relationships. Morin and Benjamin also found that for their experimental conditions, the limited water conducting ability of the crust exceeded the effect of differences in antecedent soil water on infiltration.

Other simulations of infiltration into sealing soils based on numerical solutions of the Richards' equation are shown by Whisler et al. (1979) and Moore (1981). In the former study, the effect of surface sealing is represented by time dependent changes in the saturated soil water content, saturated hydraulic conductivity, and the water entry value of the surface or sealing layer. The changes were linear in nature and were independently imposed to ascertain the relative importance of these properties on infiltration. The effect of the crust conductance on infiltration were found to be substantially larger than that of any other soil property. Moore (1981) eventually corroborated the findings of Whisler et al. (1979) of a significant impact of surface sealing on infiltration.

RESEARCH NEEDS

To quantify and refine the causes and effects of surface sealing on infiltration, substantial efforts are needed on several research fronts. These efforts should involve both experimental and theoretical studies on seal development and rain infiltration into sealing susceptible soils in which both a rigid and nonrigid subsurface soil matrix is considered. Some specific areas are

1. The effect of rainfall characteristics on seal formation, such as rainfall energy, intensity, and duration.

2. The determination of sealing susceptibility of different soils and the relationship between sealing susceptibility on one hand and intrinsic soil properties and antecedent conditions on the other hand.

3. Development of predictive infiltration relationships for heterogenous or layered soils.

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CHANNEL FLOW ROUTING IN THE SWAM MODEL

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INTRODUCTION

Channel flow routing is the process of tracing by calculation the movement of flood waves through the channel system. In general the problem consists of applying the principles of gradually varied unsteady open channel flow. The flow routing method used in SWAM was selected on the basis of the following factors: the type of hydraulic system, the type of hydrologic events moving through the system, and the type of boundary controls.

In most natural watersheds the hydraulic system embodies an arbitrary set of channel and reservoir reaches logically connected in an "oriented tree structure." SWAM regards the channel system as a cascading process in which the outflows from one or more channel reaches and diffuse sources become the input to another channel reach. The model processes one reach at a time and the different inflows and outflows are represented by time series that lie in various buffer files (Alonso and DeCoursey 1983). Channel reaches are selected such that they may be treated as prismatic elements having uniform hydraulic properties. These properties play an important role in determining the rate of travel (celerity) and rate of subsidence (attenuation) of the flood waves. Each channel reach is assigned to cross-sectional shape representative of the reach's storage properties. The amount of channel storage, in particular lateral storage, is the major factor controlling the attenuation of flood waves. Outflows from tributaries can enter a channel reach in two ways: as uniformly distributed lateral inflows and as point upstream inflows.

The hydrologic events can be such that they create fast- or slow-rising flood waves, as well as waves of short or long duration. In general, the rate of rise and duration of the hydrographs are directly related to the size of the contributing subwatershed. Channel reaches draining small upland areas frequently experience short, isolated events with dry periods in between, while lower reaches draining much larger areas can experience flow events of long duration. Furthermore, channel reaches downstream of flow control structures or intersected by a rising groundwater table may experience long periods of quasi-steady flows.

Boundary controls can exist either upstream only or upstream and downstream. Certain channel reaches may be subject to upstream control only, depending on their hydraulic properties and the magnitude of the flow event. On the other hand, in reaches upstream from reservoirs the backwater effects reduce the water surface slope to a very small value at the channel-reservoir confluence. In these instances, channel reaches are subject to both upstream and downstream control. The routing of tributaries through channel junctions may also be subject to downstream control, depending on the relative magnitude of the tributary flows. Flow routing in natural channel reaches is subject to an additional degree of freedom imposed by the nonrigid character of alluvial boundaries. Imbalances between sediment supply and transport capacity causes aggradation or degradation of the channel bed which in turn introduces variations of the reach's hydraulic properties.

The sequence of flow events passing through a channel reach forms a flow time series. The shape of the events and the statistical properties of the associated time series are governed by the factors mentioned above. The SWAM channel routing component is intended to generate consistent and accurate estimates of the short-term through long-term statistics of flow time series as well as correct simulation of individual flow events. To this end the channel component has been constructed around routing schemes that incorporate as accurate a representation of the above governing factors as permitted by computational efficiency considerations.

The balance of this paper emphasizes the rationale beind the selection of the channel flow routing schemes used in SWAM and highlights some of their more important features. A detailed presentation of these routing schemes and of results obtained for a number of channel flow simulations are given by Borah et al. (1980, 1983) and Ponce (1982).

MATHEMATICAL REPRESENTATION OF CHANNEL FLOW PROCESSES

Governing Equations

Ordinarily, the flow in a natural channel system is gradually varied, unsteady, and bounded by deformable boundaries. This type of flow can be described by the basic equations of conservation of mass and momentum, and by ancillary algorithms relating cross-sectional hydraulic properties, total sediment load, and load-bed exchanges to flow parameters. In their most general form these equations constitute a coupled nonlinear system. Although this coupled representation has the advantage of accurately considering the continuous interaction of the hydraulic and sediment phases, it admits only a tedious, time-consuming solution. For the sake of computational expediency, an approximate uncoupled representation has been adopted for the SWAM channel component (Alonso 1983). The principle of operation of the uncoupled representation is to first use the equations of water continuity and momentum conservation to compute new values of the flow variables independently of the sediment phase; then

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the sediment equations are used to update the sediment variables. This method is simpler to formulate and requires far less computational effort than the coupled method. However, the uncoupled method may lead to less satisfactory approximations in the case of very active alluvial channels. These situations, although not frequent, will obviously involve a tradeoff between accuracy and computational efficiency.

One seldom observes in nature truly straight channels in which the flow can be considered as strictly one-dimensional, namely, as following a preferential direction in a confined channel. Stream flows are most often curvilinear, following a channel bed which meanders within the valley confines. The valley itself widens and narrows in an irregular manner, and it can seldom be regarded as a simple overbank extension of the main channel. However, long experience with one-dimensional representations has shown that as long as the main channel banks are not overflowed the one-dimensional schematization works reasonably well. This is also the case when water stages are high and water inundates the overbank extensions of the main channel while flowing in a basic downstream direction defined by the valley confines. However, between these two extremes lie intermediate situations which are the most commonly encountered. Here the flow patterns during partial inundation and drainage of the valley, and the lateral momentum exchanges that result, bear little resemblance to one-dimensional behavior. Similarly, if the channel is highly irregular or if its alignment changes abruptly as in the presence of manmade structures, the one-dimensional schematization cannot provide an adequate representation of the flow pattern. In these cases water movement is not confined to a preferred direction and the flow should be treated as two-dimensional. In general, a realistic representation of streamflows calls for the use of "nested" one-dimensional and two-dimensional models to simulate situations where information needed to describe some parts of the streamflow is more detailed than the information needed for other parts of the stream. Unfortunately, the development of two-dimensional models has not progressed to the degree of reliability of their one-dimensional counterparts, and for this reason purely one-dimensional representations are used in all current streamflow models. This is also the approach selected in the SWAM channel component, in which all channel reaches are treated as one-dimensional flows.

Based on the preceding premises, the equations governing uncoupled, one-dimensional, gradually varied, unsteady channel flow are given by the Saint Venant equations:

$$A_{,t} + Q_{,x} = q_L \qquad (1)$$

$$Q_{,t} + (\beta Q^2/A)_{,x} + gAh_{,x} - gAS_o + gAS_f = 0 \qquad (2)$$

in which $Q(x,t)$ is the rate of water discharge, $A(x,t)$ is the flow area, $\beta(x,t)$ is a momentum-flux coefficient that accounts for nonuniform velocity distribution over the cross section, $q_L(x,t)$ is the rate of lateral gain/losses per unit length, $h(x,t)$ is the flow depth, g is the acceleration of gravity, $S_o(x,t)$ is the longitudinal bed slope, $S_f(x,h)$ is the longitudinal friction slope, x is the longitudinal coordinate, and t is the time variable. Lateral inflow is linked to runoff from adjacent fields, groundwater returns, and channel transmission losses.

The full momentum equation (equation 2) represents the movement of dynamic waves in which inertial, surface and body forces interact without restrictions. For this reason, the dynamic wave model is widely regarded as the most accurate model for streamflow routing applications. However, experience with this model has shown that it is also the most likely to be subject to computational instabilities which detract from its overall accuracy. Often these instabilities will be of such magnitude as to invalidate the whole process (Ponce 1982). Another disadvantage of the dynamic wave model is the need for complex and involved solution techniques. Fortunately, the dynamic wave model can be simplified further, whenever one or more terms in the dynamic equation can be neglected according to the relative magnitude of the various forces responsible for the motion. Two well known approximations lead to the kinematic and diffusion wave models. These models are much more robust than the dynamic wave model, obstensibly because of the absence of inertia in their formulation. Lighthill and Whitham (1955) made an exhaustive study of the distinctions between the larger, slower moving kinematic and diffusion waves, and the smaller, faster moving dynamic waves. They showed that for a large number of cases of practical interest, the dynamic waves are subordinated to the more permanent kinematic and diffusion waves. For these reasons, the kinematic and diffusion wave models are used in SWAM to simulate a wide range of unsteady flow conditions and channel cross-sectional characteristics. However, because of their approximate nature they cannot be used to route streamflows without regard to the particular set of flow conditions. In fact, these approximations have limits of applicability that must be observed in order to ensure an overall satisfactory accuracy.

The diffusion wave model assumes that inertia terms in equation 2 are negligible when compared to the pressure, friction, and gravity terms. Not only are they small; but in cases such as flood waves, they may actually be of the same magnitude and opposite in sign, thereby cancelling each other. The momentum equation can then by written as

$$S_f = S_o - h_{,x} \qquad (3)$$

Equations 1 and 3 can, under appropriate assumptions, be combined into one second order partial differential equation that accounts for the convection, diffusion and deformation of a

flood wave (Cunge 1969). Implicit formulation of its numerical solution requires the specification of a downstream boundary condition, which makes the diffusion wave model applicable for routing streamflows in reaches affected by downstream controls. Ponce et al. (1978) have studied the applicability of the diffusion wave model and concluded that it was applicable, provided the following inequality is satisfied

$$TS_o(g/h_o)^{\frac{1}{2}} \geqq 30 \qquad (4)$$

in which T is the flood wave duration, and h_o is the average flow depth. This equation indicates that this model may not apply for the case of routing short-duration waves in relatively flat terrain for which the dynamic contribution of the inertial terms is such that it can no longer be neglected. Nevertheless, most cases of flood waves in stream channels satisfy inequality 4. In addition, Ponce (1982) found that the diffusive wave model properly simulates unsteady flows in stream impoundments with an accuracy dependent on the flow Froude number. In spite of the robustness of the diffusion wave model, its implicit finite-difference formulation fails when flow depths are small and/or dry bed conditions develop usually during receding flows or when flow waves first appear in dry channel reaches. Whenever these conditions arise channel flow routing is carried on in SWAM using an analytical solution to the kinematic wave approximation which is not affected by the small depth problem.

The kinematic wave model assumes that the inertia and pressure terms in equation 2 are negligible compared to friction and gravity terms. Thus the momentum equation reduces to

$$S_f = S_o \qquad (5)$$

which may be interpreted as a statement of uniform flow. However, the wave-like features of the kinematic wave are introduced by the water continuity equation which contains information on the nonuniformity and unsteady nature of the flow. Combining equations 1 and 5 one obtains a nonlinear, first order, hyperbolic partial differential equation (Borah et al. 1980). This equation characterizes two important features of kinematic waves. First, they propagate only in the downstream direction, therefore restricting the application of the kinematic wave model to channels with no downstream control. Second, kinematic waves deform and become skewed but do not dissipate or attenuate. These limitations are not expected to introduce any significant deviations in the course of a typical SWAM run because the kinematic representation is restricted to very shallow flows. According to Ponce et al. (1978) the kinematic wave model is applicable to streamflows in which the following inequality is satisfied:

$$TS_oU_o/h_o \geqq 171 \qquad (6)$$

where U_o is the average flow velocity. For a given bed slope, most shallow, slower rising flood waves (larger T and smaller h_o) will in all probability satisfy the above inequality. This will be particularly true for steep channel reaches.

The possibility of quasi-steady-flow conditions appearing in a channel reach was mentioned in the introduction. In a SWAM simulation such conditions are considered to exist when all inflows to a channel reach remain constant over a day period and the ratio between any residual transient discharges and the daily mean discharge is sufficiently small. Under such conditions, the inertial terms in equation 2 become negligible and this equation reduces to equation 3. The SWAM system takes advantage of this fact in routing quasi-steady flows. The diffusion wave model is applied over six consecutive time steps, each 4 hours long, while the boundary conditions are held fixed and the residual flow transients are allowed to propagate out of the reach. The dissipative character of the diffusion wave model helps to smooth out the transients over a few time steps and prevents unrealistic discontinuities in flow-properties continuity in going from unsteady to steady flow routing.

Subsidiary Equations

The hydraulic properties of a channel reach are lumped into the friction term of the momentum equation. This term is of upmost importance because it is based on an empirical law and, as such, is the only truly adjustable term during model calibration. The friction slope in this term is computed as

$$S_f = Q^2/K^2 \qquad (7)$$

where K is the overall conveyance factor of the reach. In compact channels, that is, those without overbank sections and with uniform bed roughness, the conveyance coefficient is based on the equation

$$K(x,h) = AR^{2/3}/n \qquad (8)$$

where n is the global Manning roughness coefficient and R is the hydraulic radius. However, if the cross section has a compound shape the conveyance factor is obtained by dividing the cross section into several subsections (each subsection having a different bed roughness) and by assuming that the friction slope is constant across the channel width. Thus,

$$K(x,h) = \sum_{i=1}^{m} K_i(x,h) \qquad (9)$$

where m is the number of subsections. The reason for the different treatment of compact and compound cross sections is that the use of global

roughness coefficients in conjunction with compound cross sections is meaningless (Cunge et al. 1980).

Initial and Boundary Conditions

The equations governing the kinematic and diffusion wave approximations form two systems of nonlinear partial-differential equations. The existence and uniqueness of their solutions along a reach for a given interval of time are subject to correct specification of initial and boundary conditions.

The initial conditions must be specified along the channel reach, that is, all water levels and discharges must be known at time zero. This information is either read from a previous SWAM simulation run or it is assumed with some degree of approximation. An alternative, not part of the current SWAM version, is to use the HEC-2 (U.S. Army Corps of Engineers) or the WSP2 (U.S. Soil Conservation Service) steady-flow analysis programs to generate the initial conditions.

Boundary conditions are of two general kinds: exterior and interior. Exterior boundary conditions are externally imposed at one or both ends of a reach. They can be of the type Q(t) of h(t) as in the case of channel-reservoir confluences. When there is no downstream boundary condition available to the diffusion wave scheme, a third type of external condition is imposed in the form of a looped rating curve of the form Q(h). This is done to avoid invalidating the solution at the downstream boundary. All these three types of external conditions are fully treated as part of the overall routing scheme.

Internal boundary conditions express compatibility conditions such as continuity of discharge and/or total head. They intervene at points where the equations of motion are not applicable. The most common examples are (1) confluence of two or more tributaries; (2) sudden variation in cross sections between two reaches; (3) weir flow; (4) automatic regulation in irrigation systems. The current version of SWAM is able to handle only internal conditions created by junction of subcritical tributaries, and that in an approximated manner only. Since mutual backwater effects exist among the reaches joining at a confluence, the channel network should ideally be treated as a whole and the flow in all reaches and junctions solved simultaneously. However, for a network consisting of more than a few reaches, this approach requires an excessive amount of computer storage. In order to preserve the computational efficiency afforded by the cascading structure adopted in SWAM, the reaches are disconnected from each other by dropping the requirement of head continuity at a junction. This approximation permits treating each reach as an isolated unit while satisfying the need for continuity of water discharges at the junction.

NUMERICAL ROUTING

Numerical routing refers to the numerical methods used in the numerical integration of the governing equations. The integration is carried out along two lines: by a finite-difference method in the diffusion wave representation, and by the method of characteristics in the kinematic wave representation.

The diffusion wave model relies on a finite-difference formulation that uses a Preissman four-point implicit scheme which includes a weighting factor to control stability and convergence properties of the model. The resulting finite-difference equations are linearized using a truncated series expansion. This linearization leads to a direct, noniterative solution while preserving the nonlinearity of the physical system; that is, different flows travel at different velocities. Applying the linearized algorithm to interior and boundary points on the computational grid yields a system of linear algebraic equations. The banded nature of the coefficient matrix makes possible solving the system of equations using an efficient double sweep technique. Complete details of this routing method are given by Ponce (1982).

In the method of characteristics used by the kinematic-wave model, equations 1 and 5 are replaced by a system of ordinary differential equations. These equations are solved numerically on the characteristic grid formed by the propagation path followed by the flow waves in the space-time plane. Values of flow properties on the characteristic grid are interpolated along time lines in order to obtain flow values at the nodes of a rectangular grid consistent with the above finite-difference representation. Routing flow properties along independent characteristic paths can cause the formation of kinematic shock waves that require special treatment. In the present model an approximate shock-fitting scheme is used that preserves the effects of the shocks without the usual computational complications. Details of the characteristic routing method are presented by Borah et al. (1980).

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SWRRB FLOOD ROUTING

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INTRODUCTION

A model called SWRRB (simulator for water resources in rural basins) was developed for simulating hydrologic and related processes in rural basins. The objective in model development was to predict the effect of management decisions on water and sediment yields with reasonable accuracy for ungauged rural basins throughout the United States. To satisfy the objective, the model had to be (1) physically based and use readily available inputs (calibration is not possible on ungaged basins), (2) capable of computing the effects of management changes on outputs, (3) computationally efficient to allow simulation of a variety of management strategies without excessive cost, (4) capable of simulating long periods for use in frequency analyses, and (5) capable of operating on subdivided basins (soils, land use, management, and so forth, make subdivision necessary).

The SWRRB uses a simple flood routing method to better estimate daily flows at the basin outlet. Without flood routing, the daily basins outflow must be estimated by summing sub-basin outflows. For sub-basins with long travel times to the basin outlet, the sub-basin outflow is lagged and the peak flow is attenuated considerably. Thus, flood routing is required to simulate basin outflow realistically, particularly on large complex basins. The Variable Travel Time (VTT) method (Williams 1975) could serve this purpose, but like most flood routing methods, the VTT is fairly time consuming and requires detailed valley cross section survey information. Since SWRRB is primarily a long-term water and sediment yield simulator, a high degree of accuracy in predicting hydrographs is not as necessary as for other applications like flood control planning and flood forecasting. Also, SWRRB must operate as efficiently as possible to be useful in water resources planning that requires long-term simulations of numerous management strategies. Thus, a short-cut flood routing method based on travel time at the peak flow rate and at a low flow rate ($\sim$0.1 the peak flow rate q_p) was developed. Also, simple methods were developed for routing through ponds and reservoirs.

FLOOD ROUTING

Hydrographs must be computed at the sub-basin outlets to provide input to the routing model. Since peak runoff rate and runoff volume are computed in the surface runoff component of SWRRB, only the shape of the hydrograph is needed. The SWRRB assumes a triangular hydrograph and calculates the hydrograph base using the equation

$$t_{bi} = \frac{2Q_i}{q_{pi}} \tag{1}$$

where t_b is the triangular hydrograph base time, Q is the runoff volume, q_p is the peak flow rate, and the subscript i refers to the subbasins.

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To route the subbasin hydrographs downstream, the only information the user must supply is the channel top width, bottom width, depth, slope, length, and Manning's n value. These values should represent average channel conditions from the subbasin outlet to the basin outlet. With the given information, SWRRB computes the flow rate and velocity at the full channel depth using Manning's equation. The travel time is computed by dividing channel length by velocity. These calculations are repeated for a depth of 0.1 times the full depth. Travel time is related to flow using the nonlinear relationship

$$TT = \psi_1 q^{\psi_2} \tag{2}$$

where TT is the travel time from the subbasin outlet to the basin outlet in h, q is the flow rate in m^3/s, and ψ_1 and ψ_2 are parameters determined for each subbasin using the TT and q values calculated for full and 0.1 depth.

From equation 2 SWRRB computes the travel time at the peak flow rate and at 0.1 times the peak flow rate. The subbasin triangular hydrograph is lagged both in the beginning of rise and time to peak--a time equal the travel time at the peak flow rate. The base of the hydrograph is expanded by the difference between the 0.1 q_p travel time and the q_p travel time using the equation

$$t_{bo} = t_b + TT_{.1q} - TT_q \tag{3}$$

where t_{bo} is the hydrograph base time at the basin outlet in h, t_b is the base time at the subbasin outlet in h, $TT_{.1q}$ is the travel time for 0.1 q_p, and TT_q is the travel time for q_p in h. The peak rate at the basin outlet is then computed using the triangular hydrograph equation

$$q_{po} = \frac{2Q}{t_{bo}} \tag{4}$$

where q_{po} is the peak flow rate in m^3/s and Q is the runoff for an individual subbasin at the basin outlet in m^3. Subbasin hydrographs are summed to estimate the hydrograph at the basin outlet. Monthly peak flow rates are determined for use in developing a peak flow-frequency distribution. The flow-frequency distribution is useful in checking simulated results against measured values from the basin or from similar basins. Daily and monthly runoff volume frequency distributions are also used in checking model results.

Of course, the main purpose for estimating runoff volumes is to determine the basin's water yield. Another important purpose is that runoff volume and peak rate are used in computing sediment yield.

POND ROUTING

This component of SWRRB was designed to account for the effects of farm ponds on water yield. The water balance equation is

$$VM = VM_O + QI - QO - EV - SP \qquad (5)$$

where VM_O is the volume of water stored in all ponds within a subbasin at the beginning of the day, VM is the volume at the end of the day, QI is the inflow during the day, QO is the outflow, EV is the evaporation, SP is the seepage, and all units are m^3. The inflow, QI, is composed of surface runoff from the total pond drainage area and rainfall on the water surface area. Outflow occurs when the volume exceeds the permanent pool storage capacity and is described with the equation

$$QO = VM - VM_{mx}, \qquad VM > VM_{mx} \qquad (6)$$

$$QO = 0, \qquad VM \leq VM_{mx}$$

where VM_{mx} is the maximum permanent pool storage of all ponds in the subbasin in m^3.

The evaporation is computed with the equation

$$EV = 10.\,(\eta)\,(E_o)\,(SA) \qquad (7)$$

where η is an evaporation coefficient (~ 0.6), E_o is the potential evaporation, and SA is the surface area of all ponds in the subbasin in ha.

Seepage from the ponds is computed with the equation

$$SP = 240\,(SC)\,(SA) \qquad (8)$$

where SC is the saturated conductivity of the pond bed in mm/h.

Since pond surface area is required for computing evaporation and seepage, a relationship between surface area and volume is necessary. Data from a large number of stock ponds and small reservoirs in Texas and Oklahoma (USDA, Soil Conservation Service 1957) indicate that surface area can be calculated with the equation

$$SA = \omega_1 (VM)^{\omega_2} \qquad (9)$$

where ω_1 is a parameter ($\sim 1.3 \times 10^{-4}$) and ω_2 is a fairly constant parameter (~ 0.9). The SWRRB assumes $\omega_2 = 0.9$ and determines ω_1 for each subbasin using given SA_{mx} and VM_{mx}.

RESERVOIR ROUTING

Although this component was mainly designed to simulate flow through small reservoirs like those constructed on SCS PL566 projects, it can also be used on larger reservoirs. The reservoir water balance component is similar to the pond component except it allows flow from principal and emergency spillways. The reservoir outflow function is expressed in the equation

$$QOR = VR - VR_F, \qquad VR > VR_F \qquad (10)$$

$$QOR = (RR)(\Delta t), \qquad VR_S < VR \leq VR_F$$

$$QOR = 0. \qquad VR < VR_S$$

where QOR is the daily outflow in m^3, VR is the volume of water in the reservoir in m^3, VR_F is the reservoir capacity at the emergency spillway crest in m^3, RR is the principal spillway release rate in m^3/s, and VR_S is the reservoir capacity at the principal spillway crest in m^3.

The relationships (equations 7, 8, and 9) used to estimate evaporation and seepage from ponds are also applicable to reservoirs. However, the method for estimating ω_1 and ω_2 is slightly different. Since the surface areas and volumes for the principal and emergency spillway crest elevations are generally readily available, those values can be used for a simultaneous solution of equation 9. The resulting equations are

$$\omega_2 = \frac{\log SA_F - \log SA_S}{\log VR_F - \log VR_S} \qquad (11)$$

$$\omega_1 = \frac{SA_F}{VR^{\omega_2}} \qquad (12)$$

where SA is the reservoir surface area and subscripts F and S refer to emergency and principal spillway crest elevations, respectively.

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HYDRAULIC AND SEDIMENT TRANSPORT PROCESSES IN EPHEMERAL STREAM CHANNELS: COMPONENTS OF THE SPUR MODEL

Leonard J. Lane[1]

INTRODUCTION

Stream channels combine in complex patterns to produce channel networks and the interchannel areas. These features, among others, control the routes and rates of movement of water and sediment as runoff occurs in response to precipitation. Because these hydrologic processes are complex and highly variable in time and space, it is impossible to measure them on each watershed where information is needed. Moreover, because hydrologic processes are influenced by climate, geology and geologic materials, soils, vegetation, and land use, it is often impossible to monitor a few watersheds and extend the results over large areas. Therefore, there is a need to develop a predictive capability using mathematical models which simulate hydrologic processes. Such a model for rangeland conditions has been developed to include hydrology, vegetative development, and animal utilization. This paper describes the hydrologic components of that model (see Wight 1983).

As hydrologic processes occur over progressively larger land areas, the relative importance of stream channels increases. Therefore, there is a need to understand hydrologic, hydraulic, and sedimentation processes occurring in stream channels. Streams in natural channels in arid and semiarid regions are often ephemeral, with occasional streamflow following storm periods.

Water is often a limiting factor in arid and semiarid areas. Thus, streamflow processes, including infiltration or transmission losses in the channel bed and banks, are important components in the hydrologic cycle. Because erosion and sedimentation processes are related to hydrologic processes, there is also a need to understand sediment transport in these stream channels.

The purpose of this short paper is to describe the development and application of rather simplified procedures to simulate hydrologic, hydraulic, and sedimentation processes as used by SPUR (Wight 1983) in semiarid watersheds, with emphasis on processes in ephemeral stream channels. This paper summarizes some observations on channel processes, provides an overview of important features of those processes, and lists selected references for further study. These references provide derivations and more specific information, elaborate on these topics, and provide examples and applications.

TRANSMISSION LOSSES

As water flows in an ephemeral channel system, the of flow varies in the downstream direction as a result of variable subchannel contributions of water and sediment, channel hydraulic features, and processes such as infiltration into the channel bed and banks. Infiltration losses and abstractions, or transmission losses, are important, because they reduce the volume of runoff. Although abstractions are called transmission losses, they are an important part of the water balance because they support riparian vegetation and recharge local aquifers and regional groundwater (Renard 1970). In addition to the hydraulic and hydrologic significance of transmission losses discussed above, these losses also influence sediment transport and yield because of their affect on hydraulic processes.

Several procedures have been developed to estimate transmission losses (Babcock and Cushing 1941; Burkham 1970a, 1970b; and others). These procedures range from inflow-loss-rate equations (Burkham 1970a, 1970b; NEH-4 1972) to simple regression equations (Lane et al 1971), to simfplified differential equations for loss rate as a function of distance (Jordan 1977, Lane 1983), to storage-routing as a cascade of leaky reservoirs (Lane 1972, Wu 1972, Peebles 1975), and to kinematic wave models incorporating infiltration (Smith 1972). As a rule, the simplified procedures require less information about physical features of the channel systems, but are less general in their application. The more complex procedures may be more physically based, but they require correspondingly more data and more complex computations.

The transamission loss equations presented here represent an attempt to develop a somewhat simplified procedure for practical applications. As such, the equations represent a compromise between the more physically based deterministic models and the more simplified procedures described earlier. An empirical basis for the transmission loss equations is presented; then, the equations are derived as the solution to a first-order differential equation expressing the rate of change in runoff volume with distance in the channel.

If streamflow, without lateral inflow, occurs in a channel reach with significant amounts of transmission losses, then outflow data at a point downstream can be related to inflow data at an upstream point. If the inflow is lower than a threshold amount, all of the runoff will be lost, and no outflow will occur. Once inflow volumes exceed the threshold, then outflow volumes will increase with increasing volumes of inflow. Based on these observations, observed inflow and outflow data for a channel reach were related by regression analysis (Lane et al. 1971), resulting in an equation of the form

$$V(x,w) = \begin{cases} 0 & V_{up} \leq V_o(x,w) \\ a(x,w) + b(x,w)V_{up} & V_{up} > V_o(x,w) \end{cases} \qquad (1)$$

where

$a(x,w)$ = regression intercept (acre-ft or m^3),
$b(x,w)$ = regression slope,
$V_o(x,w)$ = threshold volume (acre-ft or m^3),
V_{up} = inflow volume (acre-ft or m^3),
x = Length of the channel reach (mi or km), and
w = average width of flow (ft or m).

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By setting $V(x,w) = 0.0$ and solving for V_{up}, the threshold volume is

$$V_o(x,w) = -a(x,w)/b(x,w) \quad (2)$$

Based upon these empirical observations and the work of Jordan (1977), Lane (1983) approximated the rate of change in runoff volume with distance as

$$\frac{dv}{dx} = -wc - wk\ V(x,w) + V_{LAT}/x \quad (3)$$

where c and k are parameters, and V_{LAT} is the volume of lateral inflow assumed to be uniform along the channel reach. The solution to equation 3 is

$$V(x,w) = \frac{-c}{k}(1-e^{-kxw}) + V_{up}e^{-kxw} + \frac{V_{LAT}}{kxw}(1-e^{-kxw}) \quad (4)$$

which is in the same form as

$$V(x,w) = a(x,w) + b(x,w)\ V_{up} + f(x,w)\ V_{LAT}/x \quad (5)$$

if we let

$$a(x,w) = \frac{a}{1-b}\ (1-e^{-kxw}) = \frac{a}{1-b}\ \left(1-b((x,w)\right) \quad (6)$$

$$b(x,w) = e^{-kxw} \quad (7)$$

$$f(x,w) = \frac{1}{kw}\ (1-e^{-kxw}) = \frac{1}{kw}\ \left(1-b(x,w)\right) \quad (8)$$

and notice that

$$b = e^{-k} \quad (9)$$

$$a = -\frac{c}{k}\ (1-b) \quad (10)$$

Thus, equations 5 through 10 are the transmission loss equations for a single channel reach when the rate of change in runoff volume with distance is described by equation 3. To compute the transmission losses in an entire channel network, these equations are applied to each channel reach or segment in the network.

It is important to note that equation 3 and its solution, given in equation 5, deal with spatial variations in transmission losses but assume steady-state loss rates with time. Of course, transmission losses are highly dynamic, and variations in time are important. Therefore, it should be noted that equations 3 and 5 reflect the steady-state assumption and, as such, emphasize spatial, rather than temporal, variations in flow rate.

OPEN CHANNEL FLOW HYDRAULICS

In anticipation of using hydraulic variables in sediment transport calculations, and for simplicity in the calculations, we make two major assumptions. These are the assumptions of rectangular-channel cross section and of normal flow. Normal flow means that depth, veloctiy, and so forth, are not changing with time at a given cross section, and are not changing with distance bewtween subsequent cross sections. That is, normal flow is both steady and uniform. Under these conditions, the average velocity in a cross section is given by the Manning equation as

$$V = \frac{a}{n}\ S^{1/2}R^{2/3} \quad (11)$$

where

V = average velocity (ft/s, m/s),
S = slope of the channel bed,
R = hydraulic radius (ft, m),
n = Manning's roughness coefficient ($s/ft^{1/3}$ or $s/m^{1/3}$) and,
a = a unit's conversion factor, 1.0 in SI units and 1.49 in English units.

The hydraulic radius for a rectangular channel is

$$R = \frac{A}{WP} = WD/(W + 2D) \quad (12)$$

where A is a cross-sectional area, WP is wetted perimeter, W is channel width, and D is flow depth. The continuity equation is then

$$Q = AV = WDV \quad (13)$$

where Q is flow rate (ft^3/s or m^3/s). The depth of flow which satisfies equations 11 and 13 is called normal depth. Flow, where depth is normal, is called normal flow.

Hydraulic Roughness

The roughness coefficient, n, in equation 11 has been tabulated for a number of channel types (Barnes 1967) and represents the resistance to flow provided by the channel bed and banks. This resistance, or roughness, is called the total roughness. Values of total roughness coefficients n_T, for various channel types are shown in table 1.

Correction for Wall or Bank Roughness

Since the flow resistance contributed by the channel banks (wall roughness) is not directly involved in transporting sediment near the channel bed, it is possible to separate its influence from the influence of the bed. Following Einstein (1942, 1944, 1950), the total cross-sectional area, A_T, is divided into an area pertaining to the wall, A_w, and an area pertaining to the bed, A_b, as

$$A_T = A_w + A_b \quad (14)$$

If the energy gradient, S, and the velocity, V, are the same for the wall and bed, and if the area is defined as the product of hydraulic radius and wetted perimeter, A = RWP, then equation 14 becomes

$$R_T(W + 2DS) = R_w(2D) + R_b(W) \quad (15)$$

By the Manning equation, hydraulic radius is

$$R = [\frac{Vn}{1.49\ S^{1/2}}]^{3/2} \quad (16)$$

where V is velocity and S is slope. Substituting

Table 1.--Approximate hydraulic roughness coefficients for open channel flow, presented as total roughness coefficient n_T

Total Manning n		Description of Channel
(.02 - .10)		Excavated or dredged channels[1]
.022	1.	Earth, straight, uniform, and clean.
.027	2.	Same, but with some short grass or weeds.
.025	3.	Earth, winding and sluggish, with no vegetation.
.030	4.	Same, but with some grass or weeds.
.080	5.	Channels not maintained; weeds and some brush.
(.03 - .10)		Natural Streams[1]
.030	1.	Clean and straight; no rifts or deep pools
.040	2.	Clean and winding; some pools and shoals.
.048	3.	Clean and winding; some weeds, stone, and pools.
.070	4.	Sluggish reaches with weeds and deep pools.
(.012 - .040)		Wide Alluvial Channels[2]
.018 - .030	1.	Ripples bed form, sediments finer than 0.6 mm, Froude Nos. < 0.37.
.020 - .040	2.	Dunes bed form, Froude Nos. 0.28 to 0.65.
.014 - .030	3.	Transitional bed form, Froude Nos. 0.55 to 0.92.
.012 - .030	4.	Antidunes bed form, Froude Nos. > 1.0.

[1]Source: Chow (1959).
[2]Source: ASCE (1966) and Simons and Richardson (1971).

equation 16 into equation 15, where V and S are common to all terms, produces

$$n_T^{3/2}(W + 2D) = n_w^{3/2}(2D) + n_b^{3/2}(W) \qquad (17)$$

with solution for the hydraulic roughness of the bed, n_b, as

$$n_b = [n_T^{3/2} + \frac{2D}{W}(n_T^{3/2} - n_w^{3/2})]^{3/2} . \qquad (18)$$

Geometric considerations suggest that the least value of R_b is 1/2 R_T, which means that, as a minimum,

$$n_b \geq (1/2)^{2/3}\ n_T \qquad (19)$$

and that as a maximum,

$$n_W \leq (\frac{W + 4D}{4D})^{2/3}\ n_T . \qquad (20)$$

Equation 18 is evaluated for n_b subject to equation 19 as a constraint (that is, $n_b \geq (1/2)^{2/3}\ n_T$), which means that the hydraulic radius of the bed is

$$R_b = [\frac{V\ n_b}{1.49\ S^{1/2}}]^{3/2} \qquad (21)$$

Table 1 can be used to estimate n_T and n_W subject to the constraints on n_W as

$$n_T \leq n_W \leq (\frac{W + 4D}{4D})^{2/3}\ n_T . \qquad (22)$$

The procedure is to select a value of n_T from the column in table 1 and to select a value of $n_w \geq n_T$ which represents conditions of the banks.

Correction for Grain Resistance

The grain, or particle resistance coefficient, n_g, is related to a representative grain size to the 1/6 power (Strickler 1923). This can be approximated as

$$n_g = 0.0132(d_{50})^{1/6} \qquad (23)$$

The hydraulic radius for grain resistance can then be estimated as

$$R_g = R_b(n_g/n_b)^{3/2} \qquad (24)$$

where R_b is obtained from equation 21, and n_b is obtained from equation 18, subject to the constraints given by equations 19 and 20.

Effective Shear Stress for Sediment Transportation

The effective shear stress for sediment transportation is given by

$$\tau = \gamma\ R_g\ S \qquad (25)$$

where

τ = effective shear stress (lb/ft^2),
γ = specific weight of water (lb/ft^3),
R_g = hydraulic radius for grain resistance (ft), and
S = energy gradient, slope of the channel bed for normal flow.

The effective shear stress, given by equation 25, will be less than the total shear stress averaged over the cross section, $\tau_T = \gamma R_T S$, because some of the total available energy is expanded on the banks due to bank roughness, and because some is expended on the bed due to form roughness.

SEDIMENT TRANSPORT CALCULATIONS

Sediment transport is assumed equal to sediment transport capacity. If sediment load exceeds transport capacity, deposition occurs; and if transport capacity exceeds sediment load, scour or erosion may occur. However, for alluvial channels with noncohesive sediments, it is common to assume sediment transport rate equal to sediment transport capacity. To avoid more elaborate sediment deposition models and channel erosion models, we assume that, as a first approximation, sediment transport rate is equal to sediment transport capacity.

Because sediment transport capacity, hereafter referred to as transport capacity, is strongly related to localized in-channel processes, it is in large part determined by the hydraulic variables described earlier. Inasmuch as the in-channel features, such as channel morphology and sediment properties as well as the hydrologic and hydraulic variables, reflect upland processes, these upland processes are reflected in the transport capacity calculations.

The Bed Load Equation

Following Einstein (1950) and others, a distinction is made between bed load and suspended load. If we assume that sediment transport rate is proportional to the water flow rate, then this distinction is somewhat arbitrary. This is because particles that travel as bed load at one flow rate may be suspended at another. The relationship between mode of transport and flow rate is a dynamically complex one and represents a continuous, rather than distinct, transition.

Nevertheless, it is reasonable to assume that larger particles travel as bed load, and that the smaller particles more easily enter suspension. Moreover, it is computationally convenient to assume a sharp distinction based on particle size. Therefore, we arbitrarily assume that all sediment larger than 0.062 mm in diameter is transported as bed load, and that finer material is transported as suspended load. Separate transport equations are derived for bed load transport and suspended load transport based on this assumption.

Using a modification of the DuBoys-Straub formula (see Graf 1971 for a complete description), transport capacity for bed-load size particles can be computed as

$$g_{sb}(d_i) = \alpha f_i\, B_s(d_i)\tau\left[\tau - \tau_c(d_i)\right] \qquad (26)$$

where

$g_{sb}(d_i)$ = transport capacity per unit width for particles of size d_i (lb/s-ft),
α = a weighting factor to insure that the sume of the individual transport capacities equals the total transport capacity computed using the median particle size,
f_i = proportion of particles in size class i,
d_i = diameter of particles in size class i(mm),
$B_s(d_i)$ = sediment transport coefficient (ft^3/lb-s),
τ = effective shear stress (lb/ft^2), and
$\tau_c(d_i)$ = critical shear stress for particles in size class i (lb/ft^2).

Values of B_s and τ_c, in English units, were determined by Straub (1935). The total bed load transport capacity is then found by summing the results from equation 26 over all the size fractions.

However, values of B_s and τ_c, as developed by Straub (1935), were for total shear stress rather than the effective shear stress, corresponding with grain resistance. Parameter estimates, using effective shear stress, are given by

$$B_s(d_i) = 40.0/(d_i)^{1.5} \qquad (27)$$

and

$$\tau_c(d_i) = \begin{cases} 0.0022 + 0.010\, d_i & .062 \le d_i \le 1.0 \\ -0.0078 + 0.020\, d_i & 1.0 < d_i \end{cases} \qquad (28)$$

where d_i is the representative particle diameter (mm). Equations 27 and 28 were calibrated with observed sediment transport data from the Niobrara River in Nebraska (Colby and Hembree 1955) for particle sizes up to 2.0 mm. Therefore, equations 27 and 28 have not been evaluated for particles larger than 2.0 mm in diameter. Because the weighting factor, α, in equation 26 insures that the sum of the individual transport capacities equals the total transport capacity -- computed using the median particle size, d_{50}, in equations 26 through 28 -- the model has not been evaluated for values of d_{50} in excess of 1.0 mm.

The Suspended Load Equation

Bagnold (1956, 1966) proposed a sediment transport model based on the concept of stream power as

$$i_s = P\,\frac{e_s\, u_s}{v_s}(1 - e_b) \qquad (29)$$

where

i_s = suspended sediment transport rate per unit
P = τV = available stream power per unit area of the bed (lb/s-ft),
e_s = suspended load efficiency factor,
e_b = bed load efficiency factor,
u_s = transport velocity of suspended load (ft/s), and
v_s = settling velocity of the particles (ft/s).

Now, if u_s is assumed equal to the mean velocity of the fluid, V, then equation 29 is of the form

$$g_{sus} = f_{sc} \cdot CAS \cdot \tau V^2 \qquad (30)$$

where

g_{sus} = suspended sediment transport capacity (lb/s-ft),
f_{sc} = proportion of particles smaller than 0.062 mm in the channel bed material,
τ = effective shear stress (lb/ft^2),
V = average velocity (ft/s), and
CAS = suspended sediment transport coefficient (s/ft).

The suspended sediment transport coefficient, CAS, incorporates the efficiency parameters and the settling velocity of the suspended particles. Values of CAS have been determined by calibration with observed data. However, because of the scarcity of observed data and the interaction of the efficiency parameters and settling velocity, and their interaction with flow dynamics, values of CAS are not well specified by measurable physical characteristics.

APPLICATIONS AND DISCUSSION

Procedures have been outlined which can be used to estimate reductions in runoff due to transmission losses to estimate hydraulic variables in open channel flow, and to compute sediment transport capacity in alluvial channels. Various aspects of these procedures have been applied to compute runoff and sediment yield on semiarid rangeland watersheds.

Lane (1982a) used the transmission loss equations to develop a simplified routing procedure as part of a basin-scale hydrologic model. The model was used to simulate runoff volume and peak discharge rates for individual storm events. Example applications included estimation of flood frequency curves for semiarid rangeland watersheds. Lane (1982b) used the basin-scale runoff estimation model, together with a hydrograph estimation technique and the sediment transport equations, to estimate sediment yield from semiarid watersheds. More recently, the transmission loss and sediment transport equations were modified to provide the channel component of a hydrologic model used as part of a range resource model (Renard et al. 1983).

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SURFACE IRRIGATION MODELS

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Surface irrigation models are a special case of overland flow models. They pertain to the application of water to a field for irrigation. Boundary conditions are imposed by the field geometry (slope, cross section, and physical upstream and downstream boundaries). Flow duration and rate are assumed to be controllable, and surface roughness and infiltration (which vary over the irrigation season) are assumed to be known for a particular irrigation event. The models seek to determine the net amount of water entering the soil profile and the runoff by tracking water advance and recession across the field. A number of mathematical models have been developed to describe this process. These different models vary in their complexity on how they describe the flow and how they solve the governing equations of flow which ultimately determine the profile of infiltrated water and runoff.

The earliest models developed were the volume balance models. These models are based on continuity and make some simplifying assumptions about the surface water (water above soil surface) profile and subsurface water profile. It is implicitly assumed that infiltration is spatially uniform (but still time dependent) and that the inflow rate is uniform over some specified period. If all these assumptions hold, these models are reasonable. Unfortunately, these models are extremely difficult to apply in "new" areas, since the shapes of the profile may vary dramatically from site-to-site. These models have an advantage in that they are solved by direct numerical calculations; however, they are of little general usefulness.

The slightly more sophisticated approach is represented by kinematic wave models (KW). These models keep track of continuity but also make the assumption that there is a unique, known relationship between depth and discharge. This essentially assumes that "normal depth" exists everywhere in the profile, or that the friction slope equals the bottom slope. Several types of these models have been developed utilizing a variety of solution techniques, including (1) numerical solutions such as the method of characteristics, or finite difference techniques (for example, with double sweep) and (2) analytical solutions of the governing equations (a new solution being required for each case). These models are applicable to relatively steep slopes. As the slope approaches zero, these models yield unrealistic results.

The next level of model sophistication is represented by the zero-inertia or equilibrium models (ZI). These models start with the full hydrodynamic equations of flow (commonly, the Saint Venant equations) and eliminate the inertial (acceleration) terms--hence, the name zero-inertia. This is equivalent to assuming a balance (or equilibrium) of forces on any volume of water in the surface profile (cell). The momentum equation is reduced to a form in which the difference between the friction and bottom slopes (which was zero for the kinematic wave models) is equal to the change in depth with distance. These models are solved by numerical techniques (either finite difference form or integral form). Computational difficulties have been encountered with the finite difference form of the ZI models when computing recession on steep slopes.

The most sophisticated irrigation models are called the complete models. These models are complete in the sense that they solve the complete equations of continuity and momentum. The models developed to date have all been solved by the method of characteristics. The computer programs for these models are complex and extremely expensive and time-consuming to run. These disadvantages could be reduced somewhat by solving the integral form of the equations (for example, by the Newton-Ralphson technique). The results from these models are used as standards of comparison for the other models.

In 1960, the SCS and ARS held a joint symposium on irrigation modeling at Fort Collins, CO. At that time only volume balance models existed. A number of complete hydrodynamic models were developed in the 1960's and extended into the 1970's. None of these are used very much because of their cost and complexity. In 1972, Roger Smith produced an excellent kinematic wave model (solved by the method of characteristics). This model is still in use, although a comprehensive computer program has never been documented. In 1977, Strelkoff and Katopodes published the first zero-inertial model for border irrigation. The solution technique linearized the continuity and momentum equations for an oblique grid and solved them by the double sweep technique. The model (and computer program) has been modified considerably since then. This modified program has been used by numerous researchers for a number of studies. Several individuals have extended the ZI model to furrows.

Numerous computer programs for KW and ZI models are in use with little or no documentation. A comprehensive border irrigation program, BRDRFLW (short for border flow), was recently developed with four different models of border irrigation flow: a KW model solved by the method of characteristics, a linearized ZI model solved with the double sweep, a fully nonlinear ZI model, and a hybrid ZI/KW model. This hybrid model uses the ZI model (either linear or nonlinear) from the start of advance to the start of recession and the KW model afterward. This hybrid model is used to eliminate the computational difficulties of the ZI model on steep slopes.

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Only general guidelines on which model to use have been developed. The border flow program allows for variable bottom slopes and inflow hydrographs and for either open or blocked field ends. The program can be run in English, metric, or nondimensional units. BRDRFLW also allows a variety of roughness and infiltration functions, different levels of diagnostic output, and plotting routines.

The output from BRDRFLW includes advance, recession, runoff, infiltration, and deep percolation distribution; it also includes a number of efficiency and uniformity parameters which are functions of the minimum infiltrated depth, the low quarter infiltrated depth, and a user-specified desired application depth. If desired, additional information on flow depths and runoff rates can be output. This program and its documentation are available from the author.

A comprehensive surface irrigation (SRFIRRG) program is being developed with options for handling border or furrow irrigations, models from KW to complete hydrodynamic, surge flow and a variety of other parameters. This program should be available by late 1984 or early 1985.

These programs are useful for a variety of purposes, including assistance with irrigation system design, development of irrigation management strategies, evaluation of current practices, determination of important design considerations, development of design charts, and analyzing variable soil conditions such as spatial variability or surge flow.

The ZI models have been used by a number of researchers for a variety of purposes, particularly the study of level basins. The new irrigation programs (BRDRFLW and SRFIRRG) will add new dimensions to the effective usefulness of irrigation models.

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MODELING WATER MOVEMENT AND THERMAL STRUCTURE IN AGRICULTURAL IMPOUNDMENTS

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INTRODUCTION

The approach to any modeling effort is determined jointly by the system being modeled and the objectives of the model. Models of physical processes in small reservoirs could be generated for purposes ranging from the testing of theories about fundamental physical processes in small water bodies, for generating forcing functions in ecological models, to assessing the role of impoundments in basin-scale land-management practices.

In the context of the Small Watershed Model (SWAM), impoundments are viewed as components of a watershed. In that context, a major interest is in the quantity and quality of water leaving a stream segment defining the lower boundary of the catchment. An impoundment model must therefore be able to realistically simulate the quantity of water flowing out of the reservoir to downstream segments at any time, as well as the concentrations of any pollutants of interest.

Clearly, simulation of the quality of water leaving a reservoir requires an understanding of in-lake processes, since the residence time of water in even the smallest of impoundments is long enough for some chemical transformations and sediment settling to occur. That is, an impoundment cannot be treated simply as a term for smoothing a hydrograph. In addition, there may be circumstances in which a model user is interested in conditions within a farm pond. Surveys show that about 80 percent of farmers list stock watering as a primary reason for constructing ponds; hence, volume of storage and perhaps also quality of water in a pond at any time may be of interest. The Soil Conservation Service constructs impoundments as part of flood control programs; hence, the stage during an extreme event may be a quantity of interest. Thus, the objectives of the model require that physical, chemical, and biological processes occurring within the reservoir be simulated in detail.

The model FARMPND, the impoundment submodel for SWAM, is a mechanistically based model consisting of routines for water storage and routing, vertical temperature structure, suspended sediment transport and settling, and light penetration. Chemical and biological components are included for simulating concentrations of pesticides and nutrients (see pages , this volume). Individual components of FARMPND are described below. The model is an adaption of the Minnesota Lake Temperature Model, RESQUAL. Additional details about the theory behind the mathematical formulations can be found in publications relating to that model (Stefan and Ford 1975a,b, Schiebe 1976, Dhamotharan et al. 1978, Ford and Stefan 1980, Dhamotharan et al. 1981, Stefan et al. 1982a,b).

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TIME AND SPACE SCALES

The physical characteristics of farm ponds place constraints on the model structure. Farm ponds range in size from about 0.1 to 5 ha. By most criteria (Ford and Thornton 1979) this size would qualify for one-dimensional modeling (in the vertical). Larger size functions of suspended sediments could be expected to form longitudinal gradients, resulting in delta formation (that is, a two-dimensional problem), but simulation of that process would depend on the details of the geometry of each individual reservoir. Solution of the one-dimensional advective-diffusion equation can be expected to adequately predict the concentration of fine clays in the outflow.

The time scale for modeling physical processes in reservoirs depends on the process being considered. Flood waves resulting from localized heavy thunderstorms may propagate through a reservoir on a scale of several hours. The coarser fractions of suspended sediment entering with such an event may settle out in minutes, while the finer fractions may remain in suspension for weeks. The thermal energy budget for a shallow reservoir can be considered to be in balance only on a time scale of 1 day. This is because of the necessity of handling solar energy adsorption, diffusion, wind mixing, and penetrative convection separately. Since the parameters in the advective-diffusion equation for suspended sediment depend on the thermal structure, the model FARMPND routinely operates at a time step of 1 day.

MODEL CONCEPTS

Water Budget

The continuity equation for flow through a small reservoir can be written

$$dV/dt = Q_{in} - Q_{out} \qquad (1)$$

where dV/dt is the rate of change of storage, and Q_{in} and Q_{out} are the inflow and outflow rates, respectively. Evaporation and direct precipitation are treated separately as surface fluxes. Inflow is a forcing function that is supplied by the stream, overland flow, and groundwater components of SWAM.

To solve equation 1, it is necessary to rewrite

the equation in terms of stage. For most lakes and reservoirs, storage can be represented as a power function of stage of the form

$$V = ah^{b} \qquad (2)$$

where h is the stage and a and b are coefficients (Schiebe 1976). Coefficients in equation 1 can be estimated by linear regression of log(V) against log(h) if a survey of the impoundment is available. Otherwise, coefficients can be estimated less precisely if volume and stage are known at two points, e.g. at the principal spillway and emergency spillway.

Outflow is a power function of the head above the outflow structure and, hence, of stage. Q_{out} can be represented

$$Q_{out} = c(h-h_0)^{d} \qquad (3)$$

where h_0 is the stage of the principal spillway, and c and d are coefficients. Values of c and d in equation 3 for various outflow structures can be found in Chow (1959).

Substituting for V and Q_{out} in equation 1 gives an equation with h as the only dependent variable. The equation can be nondimensionalized by normalizing volume and stage to their values at the principal spillway. The nondimensional stage, h*, and nondimensional volume, V*, are given by

$$h^* = h/h_0 \qquad (4a)$$

$$V^* = V/V_r = ah^{b}/(ah_0{}^{b}) = h^{*b} \qquad (4b)$$

where V_r is a reference volume taken as the storage at the principal spillway. These substitutions give an equation for non-dimensional stage of the form

$$dh^*/dt = [Q_{in}/V_r - (ch_0{}^{d}/V_r)(h^* - 1)^{d}]^{1/b} \qquad (5)$$

In FARMPND, equation 5 is solved by a fourth-order Runge-Kutta numerical integration. A valid solution is subject to the constraint that if the stage was above the principal spillway at the start of a time step, the outflow may not take the stage below it. The time step is divided in half as necessary until this condition is satisfied.

Density Current Routing

It frequently occurs that the density of water flowing into a reservoir is different from that of the water in the reservoir. This may be due to differences in any combination of temperature, dissolved solids, or suspended solids. The inflow may enter as a overflow, as an underflow, or if the receiving water is stratified, as an interflow. In addition, a plunging density current entrains water from the surrounding fluid as it flows toward its isopycnic level, thereby diluting the density current with ambient water.

For the purpose of calculating temperature profiles and routing the density current, the reservoir is divided into a number of horizontal slabs. Each segment has an associated value of temperature, suspended sediment and chemical concentrations, as well as morphometric characteristics, that is cross-sectional area, volume and thickness. Inflow and outflow are treated as additions to and subtractions from the layers, so that the volume and thickness of layers may change during a simulation. Minimum and maximum allowable thicknesses are built into the routine to prevent the formation of discontinuities. Layers are merged or split as necessary to keep the thickness of layers within the specified bounds.

As water flows into the reservoir, it seeks a layer with density equal to its own. As the inflow moves towards its isopycnic layer, it entrains water within the plunging region from the layers it flows past. The amount of entrainment by a plunging density current is a complex function of the morphometry (principally slope), stratification, buoyancy of the current, and turbulence. A densimetric Froude number criterion is used to determine the entrainment ratio for each layer in the plunging region. Entrainment is not calculated for inflow entering the mixed layer. Details of the theory and equations are given by Akiyama and Stefan (1981) and Stefan et al. (1982).

Stratification and Mixing

Prediction of the temperature profile consists of separate routines for calculating the transfer of heat at the water surface and for distributing the heat vertically by the action of wind mixing. Mixing is determined by a stability criterion that compares the total kinetic energy available for mixing with the incremental potential energy of the temperture profile.

Thus, mixing is intermittent occurs only when sufficient wind energy is available.

Processes modeled in the net transfer of radiation of the water surface included (1) radiation heat transfer at the water surface and absorption in the water column, (2) heat losses from the water surface by back-radiation, evaporation and convection, and natural convection, (3) heat transfer below the surface mixed layer by turbulent diffusion.

The one-dimensional transient diffusion equation for heat in a water column is

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_z \frac{dT}{dz}\right) + \left(\frac{S}{\rho c V}\right) \qquad (6)$$

where T = water temperature, t = time, K_z = vertical heat diffusivity, S = solar radiation absorbed at depth z, ρc = specific heat per unit volume, and V = volume of layer. Energy absorbed in the topmost layer is given by

$$S(1) = (1-r)B\ H_s + H_{an} - H_{br} - H_e - H_c \qquad (7)$$

where H_s = incoming solar radiation, B = near surface absorption coefficient to account for enhanced absorption of red and near infrared wavelengths, r = reflectivity, which is a function of suspended sediment concentration at the surface, H_{an} = net atmospheric radiation, H_{br} = back-radiation, H_e = evaporative heat flux, and H_c = convective heat flux. The individual terms in equation 7 are evaluated from empirical relationships using standard meteorological observations as input. Radiation penetrating to layers below the surface is attenuated exponentially with depth.

After absorption and diffusion has been calculated, the entrainment of layers below the mixed layer is determined from the kinetic energy balance. At each time step, the kinetic energy available for mixing is compared with the potential energy of the stratification. If the kinetic energy exceeds the potential energy, then a layer is entrained into the mixed layer and the comparison is repeated until the potential energy equals of just exceeds the kinetic energy.

Kinetic energy available for mixing is computed from the wind stress on the surface. The effective wind speed is corrected for fetch, assuming that a logarithmic boundary surface grows outward from the shore. Surface shear stress is assumed to be proportional to the square of the windspeed measured at a height of 10 m, and the kinetic energy is proportional to the cube of the shear velocity.

SAMPLE SIMULATIONS

The detailed input necessary to run the model was not readily available for any farm impoundments. The model has been calibrated and tested for Lake Chicot, a large oxbow of the Mississippi River in southern Arkansas. Computed and observed lake stages are shown in figure 1.

In this version of the model, the stage was computed by finite-difference solution of equation 1 using the stage at the start of a time step to compute outflow rather than the numerical integration procedure outlined here. Nevertheless, predicted stage follows the measurements closely.

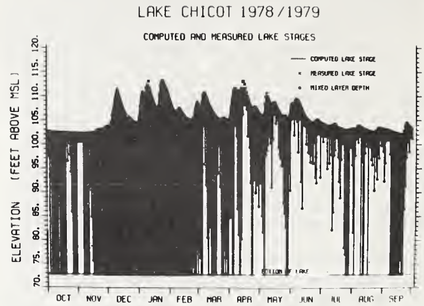

Figure 1.--Predicted and observed lake stages and mixed layer depth for Lake Chicot, AR, 1978-1979. From Stefan et al. 1982a.

Predicted and observed temperatures at the surface and 7 m are compared in figure 2. Computed and observed temperature ranges for specific days may differ, but the seasonal trend is well reproduced. In addition, certain qualitative features, such as the intermittent nature of the onset of vertical stratification in the spring, are correctly predicted by the model.

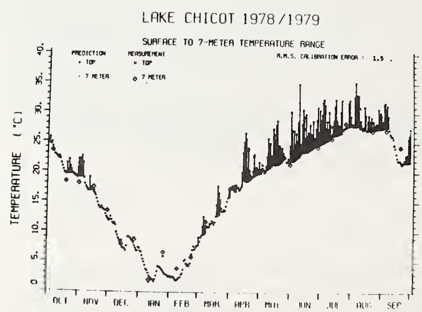

Figure 2.--Predicted and observed temperature ranges from surface to 7 m, Lake Chicot, AR, 1978-1979. From Stefan et al. 1982a.

Inflow and stage records are available for an impoundment near Chickasha, OK.

Stage was simulated from measured inflow records for the month of June, 1981, which is shown with measured values in figure 3.

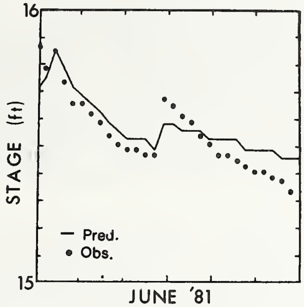

Figure 3.--Predicted and observed stages, Site 11, Little Washita river near Chickasha, OK.

The simulated hydrograph responds to the two major storms during the period but is dampened relative to the measured points, probably because the morphormetric equation overpredicts the volume and surface area of the impoundment at the principal spillway.

CONCLUSIONS

Simulation of water movement and thermal stratification in agricultural impoundments should be feasible provided the necessary input values and parameters are available. For field application of the model, input data is likely to be the limiting factor, since the detailed surveys needed to generate the morphometric equation are likely to be available only for intensively studied reservoirs. In addition, daily meteorological observations are required, including dew point (or relative humidity), windspeed, percent cloud cover, and solar radiation. For purposes of forcasting long term trends, these data may be simulated; in this application the model is likely to prove most useful.

Future research should be aimed at verifying the model in agricultural impoundments. In particular, it will be necessary to test the applicability of assumptions about the transfer of wind energy across the water surface for water bodies the scale of farm ponds. Alternative criteria for determining mixed-layer deepening have been proposed (Harleman 1982). These should be tested if current criteria prove deficient.

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HEAT TRANSPORT EQUATION FOR THE INSTREAM WATER TEMPERATURE MODEL

Fred D. Theurer[1]

INTRODUCTION

The Soil Conservation Service (SCS), in cooperation with the Instream Flow and Aquatic Systems Group (IFG) of the Western Energy and Land Use Team (WELUT), U.S. Fish and Wildlife Service, has developed a model, with complete documentation, to predict instream water temperatures using either historical or synthetic hydrological, meteorological, and stream geometry conditions. The model is applicable to any size watershed or river basin with a stream network of any stream order and complexity. It incorporates many features, including--

1. A heat transport model to predict the average mean daily temperature and the average diurnal fluctuations of water temperature as a function of stream distance.

2. A heat flux model to predict the energy balance between the water and its surrounding environment.

3. A solar model to predict solar radiation penetrating the water as a function of latitude, time of year, and meteorological conditions.

4. A shade model to predict the solar radiation-weighted shading due to both topography and riparian vegetation.

5. Meteorological corrections to predict the changes in air temperature, relative humidity, and atmospheric pressure as a function of change in elevation.

6. Regression aids to smooth and/or fill missing water temperature data collected at headwater and internal validation/calibration locations.

The documentation--Instream Flow Information Paper No. 16 (Theurer et al. in prep.)--describes these features and subsidiary features, such as statistical aids and guidance regarding basic data sources, and how to use the model in ungauged watersheds.

The model can and has been used satisfactorily to evaluate the impact on instream water temperatures for the following factors:

1. Riparian vegetation--existing, previous, and proposed.

2. Reservoir releases--discharge rates and temperatures.

3. Stream withdrawals and returns.

The model has been used in large basins, for example, the Upper Colorado River Basin, to study the impact of water temperature on endangered species (Theurer et al. 1982b). It has been used in smaller, ungauged watersheds, for example, in the Tucannon River in the Columbia River Basin, to study the impacts of riparian vegetation on salmonid habitat (Theurer 1983). It has also been used several times to evaluate the impact of reservoir releases on water temperature immediately below dams.

Software for various solution techniques are available through IFG. This software ranges from programs for hand-held calculators to programs for large-scale computers. The selection of the proper solution technique depends upon the complexity of the application, volume of computations involved, and user availability of hardware.

This paper describes development of the heat transport equation and some validation results.

HEAT TRANSPORT

The heat transport model is based upon the dynamic-temperature/steady-flow equation. This equation, when expressed as an ordinary differential equation, is identical in form to the less general steady-state equation. However, it requires different input data and requires tracking the mass movement of water downstream. The simultaneous use of the two identical equations with different sets of input is acceptable since the actual water temperature equals the average daily water temperature twice each day--once at night and then again during the day.

The steadystate equation assumes that the input parameters are constant for each 24-hour period. Therefore, the solar radiation, meteorological, and hydrological parameters are 24-hour averages. It follows, then, that the predicted water temperatures are also 24-hour averages. Hence, the term "average daily" means 24-hour averages--from midnight to midnight for each parameter.

The dynamic model allows the 24-hour period to be divided into night and day times. While the solar radiation and meteorological parameters for nighttime and daytime are different, they are considered constant. Since the dynamic model is a steady flow model, the discharges are constant over the 24-hour period.

It can be visualized that the water temperature would be at a minimum at sunrise and continually rise during the day such that the average daily water temperature would occur near noon. At

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sunset, the water temperature would be at its maximum, then it would begin to cool such that average daily temperature would again occur near midnight. Just before sunrise the temperature would return to a minimum.

The steady-state equation, with input based upon 24-hour averages, can be used to predict the average daily water temperatures throughout the entire stream network. Since these average daily values actually occur near midnight and midday, the dynamic model can be used to track the column of water between midnight and sunrise and between midday and sunset to determine the minimum night-time and maximum daytime water temperature, respectively. Of course, the proper solar radiation and meteorological parameters reflecting night and daytime conditions must be used for the dynamic model.

The minimum/maximum simulation requires that the upstream average daily water temperature stations at midnight/midday for the respective sunrise/sunset stations be simulated. This step is a simple hydraulic procedure requiring only a means to estimate the average flow depth.

Dynamic-Temperature/Steady-Flow

A control volume for the dynamic-temperature/steady-flow equation is shown in figure 1. It allows for lateral flow. To satisfy the fundamental laws of physics regarding conservation of mass and energy, the heat energy in the incoming water less the heat energy in the outgoing water plus the net heat flux across the control volume boundaries must equal the change in heat energy of the water within the control volume. The mathematical expression is

$$\{[\rho c_p(QT)_i - \rho c_p(QT)_o] + [\rho c_p q_\ell T_\ell \Delta\chi] + [(\bar{\beta}\Sigma H)\Delta\chi]\}\Delta t = \{[\rho c_p(AT)/\partial t)]\Delta t\}\Delta\chi \qquad (1)$$

where ρ ≡ water density, M/L^3

c_p ≡ specific heat of water, E/M/T

Q ≡ discharge, L^3/t

T ≡ water temperature, T

q_ℓ ≡ lateral flow, L^2/t

T_ℓ ≡ lateral flow temperature, T

χ ≡ distance, L

t ≡ time, t

A ≡ flow area, L^2

i ≡ inflow index

o ≡ outflow index

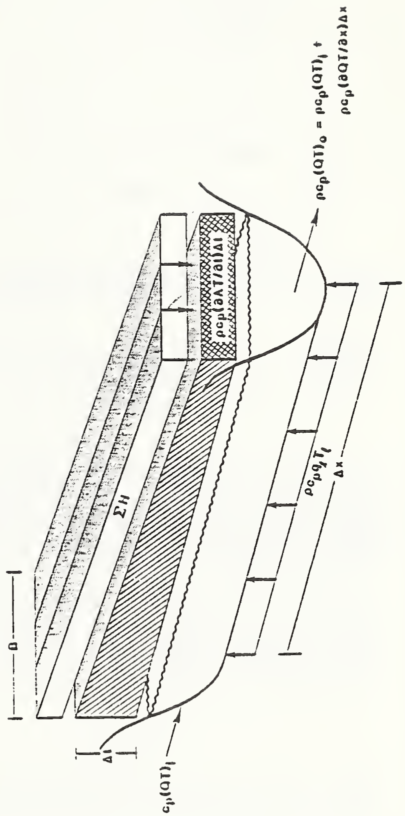

Figure 1.--Dynamic energy control volume.

$\bar{\beta}$ ≡ average stream top width, L

ΣH ≡ net heat flux across control volume, $E/L^2/t$

note: units are

M - mass

T - temperature

L - length

t - time

E - heat energy

Equation 1 reduces to

$$\partial(AT)/\mu t + \partial(QT)/\partial\chi = q_\ell T_\ell + (\beta\Sigma H)/\rho c_p) \tag{2}$$

Assuming steady flow ($\partial A/\partial t=0$), letting $H_n = \beta\Sigma H$, recognizing $q_\ell \equiv \partial Q/\partial\chi$, and dividing through by Q leads to

$$\underbrace{(A/Q0\ (\partial T/\partial t)}_{\text{dynamic term}} + \underbrace{\partial T/\partial\chi = (q_\ell/Q)(T_\ell-T) + H_n/(Q\rho c_p)}_{\text{steady-state equation}}$$

$$\xleftrightarrow{\text{dynamic-temperature/steady-flow equation}}$$

If the dynamic temperature term is neglected ($\partial T/\partial t = 0$), then the steady-state equation is left. Since the steady-state equation contains only a single independent variable χ, it converts directly into an ordinary differential equation with no mathematical restrictions:

$$dT/d\chi = [(q_\ell/Q)(T_\ell-T)] + [H_n/(Q\rho c_p)] \tag{4}$$

If the dynamic temperature term is not neglected ($\partial T/\partial t \neq 0$), then equation 3 can still be solved using the classical mathematical technique known as the Method of Characteristics. If, for notational purposes only, we substitute

$$\Phi \equiv (q_\ell/Q)(T_\ell-T) + H_n/(Q\rho c_p) \tag{5}$$

into equation 3 and use the definition of the total derivative for the dependent variable T, a resulting pair of dependent, simultaneous, first-order partial-differential equations emerges:

$$(A/Q)(\partial T/\partial t) + (1)(\partial T/\partial\chi) = \Phi \tag{6}$$

$$(dt)(\partial T/\partial t) + (d\chi)(\partial T/\partial\chi) = dT \tag{7}$$

Since the equations are dependent, the solution of the coefficient matrix is zero; that is,

$$\begin{matrix} (A/Q) & 1 \\ dt & dx \end{matrix} = 0$$

which leads to the characteristic line equation

$$d\chi = (Q/A)dt \tag{8}$$

For the same reason, the solution matrix is also zero; that is,

$$\begin{matrix} \Phi & 1 \\ dt & d\chi \end{matrix} = 0$$

which leads to the characteristic integral equation

$$dT/d\chi = [q_\ell/Q)(T_\ell-T)] + [H_n/(Q\rho c_p)] \tag{9}$$

when Φ is replaced by its original terms of equation 5.

Equation 9 is identical in form to equation 4 and is valid for dynamic temperature conditions when solved along the characteristic line equation (equation 8). This presents no special problem since equation 8 simply tracks a column of water downstream--an easily simulated task.

Closed-form solutions for the ordinary differential equation forms (equations 4 and 9) of the dynamic-temperature, steady-flow equations are possible with two important assumptions: (1) uniform flow exists and (2) first-and second-order approximations of the heat flux (H_n) as a function of water temperature are valid.

The first-order approximation of H_n is

$$H_n = K_1\ (T_e-T) \tag{10}$$

The second-order approximation of H_n is

$$H_n = K_1(T_e-T) + K_2(T_e-T)^2 \tag{11}$$

where H_n ≡ heat flux as a function of water temperature, $E/L^2/t$

T ≡ water temperature, C

T_e ≡ equilibrium water temperature, C

K_1 ≡ first-order thermal exchange coefficient, $E/L^2/t/C$

K_2 ≡ second-order thermal exchange coefficient, $E/L^2/t/C^2$

First-order Solutions

First-order solutions are possible for all three cases of q_ℓ: case 1, $q_\ell>0$; case 2, $q_\ell<0$; and case 3, $q_\ell=0$.

Case 1, $q_\ell>0$:

The ordinary differential equation (4) with the first-order substitution for H_n (equation 10) is

$$dT/d\chi = [(q_\ell/Q)(T_\ell - T)] + [K_1(T_e - T)\bar{\beta}/(\rho c_p Q)] \quad (12)$$

Since $Q = Q_o + q_\ell \chi$, equation 12 becomes

$$[Q_o + q_\ell \chi] dT/d\chi = \{[q_\ell T_\ell] + [(K_1\bar{\beta})/(\rho c_p)]T_e\} - \{q_\ell + [(K_1\bar{\beta})/(\rho c_p)]\}T \quad (13)$$

If we let $a = [q_\ell T_\ell] + [(K_1\bar{\beta})/(\rho c_p)]T_e$

$b = q_\ell + [(K_1\bar{\beta})/\rho c_p)]$

then equation 13 becomes

$$(Q_o + q_\ell \chi)\ dT/d\chi = a - bT \quad (14)$$

Using separation of variables,

$$\int_{T_o}^{T_w} \frac{dT}{a-bT} = \int_0^{\chi_o} \frac{dx}{Q_o + q_\ell \chi}$$

and the solution is

$$T_w = (a/b) - [(a/b) - T_o][1 + (q_\ell \chi_o/Q_o)]^{(-b/q_\ell)} \quad (16)$$

Case 2, $q_\ell<0$

If $q_\ell<0$, then $T_\ell=T$ and equation 12 becomes

$$[Q_o + q_\ell \chi_o]\ dT/d\chi = [(K_1\bar{\beta})/(\rho c_p)]T \quad (17)$$

The solution is

$$T_w = T_e - [T_e - T_o][1 + (q_\rho \chi_o/Q_o)]^{[(q_\ell - b)/q_\ell]} \quad (18)$$

Case 3, $q_\ell = 0$

If $q_\ell = 0$, then $Q=Q_o$ and equation 12 becomes

$$dT/d\chi = [(K_1\bar{\beta})/(\rho c_p Q_o)]T \quad (19)$$

The solution is

$$T_w = T_e - [T_e - T_o] \exp[-(K_1\bar{\beta}\chi_o)/\rho c_p Q_o)] \quad (20)$$

Second-order Solutions

A second-order solution for case 3 is as follows:

Letting $q_\ell=0$ and using equation 11 results in

$$dT/d\chi = [K_1(T_e - T) + K_2(T_e - T)^2]\bar{\beta}/(\rho c_p Q) \quad (21)$$

The solution is

$$T_w = T_e - \frac{(T_e - T_o)\ \exp[-(K_1\bar{\beta}\chi_o)/(\rho c_p Q)]}{1 + (K_2/K_1)(T_e - T_o)\{1 - \mathrm{ecp}\ [-(K_1\beta\chi_o)/(\rho c_p Q]\}}$$

Using the first-order solution and making second-order corrections according to the form suggested by equation 22 results in

$$T_w = T'_e\ [(T'_e - T_o)R]/[1+(K_2/K_1)(T'_e - T_o)(1-R)] \quad (23)$$

where $a = [q_\ell T_\ell] + [(K_1\bar{\beta})/(\rho c_p)]T_e$

$b = q_\ell + (K_1\bar{\beta})/(\rho c_p)$

Case 1, $q_\ell>0$

$T'_e = a/b$

$R = [1 + (q_\ell \chi_o/Q_o)]^{(-b/q_\ell)}$

Case 2, $q_\ell<0$

$T'_e = T_e$

$R = [1 + (q_\ell \chi_o/Q_o)]^{[(q_\ell - b)/q_\ell]}$

Case 3, $q_\ell = 0$

$T'_e = T_e$

$R = \exp[-(b\chi_o)/Q_o]$

Diurnal Fluctuations

The following relationships can be solved explicitly at any study site or point of interest to determine the maximum rise of the water temperature above the average. They are based upon the fact that the actual water temperature equals the average temperature twice each day, that the average water temperature occurs approximately halfway through the day, and that the remainder of the day the water temperature increases steadily to a maximum near sunset. The same logic is used for determining the minimum water temperature by substituting nighttime conditions for daytime.

$$d = \{[Q/\bar{\beta})n]/[\sqrt{\bar{S}_e}]\}^{3/5} \quad (24)$$

$$t_\chi = (S_o/2)\ 3600 \quad (25)$$

$$T_{o\chi} = T_{ed} - \{(T_{ed} - T_{wd}) \exp[(K_d t_\chi)/\rho c_p d)]\} \quad (26)$$

$$T_{w\chi} = T_{e\chi} - \{(T_{e\chi} - T_{o\chi}) \exp[-(_\chi t_\chi)/(\rho c_p d)]\} \quad (27)$$

where $d \equiv$ average flow depth, m

$n \equiv$ Manning's n-value

$Q \equiv$ discharge, m^3/s

$\bar{\beta}$ ≡ average top width, m

S_e ≡ energy gradient, m/m

t_χ ≡ travel time from noon to sunset, s

S_o ≡ duration of possible sunshine from sunrise to sunset, hours

T_{ed} ≡ equilibrium temperature for average daily conditions, C

$T_{e\chi}$ ≡ equilibrium temperature for average daytime conditions, C

T_{wd} ≡ average daily water temperature (at solar noon) at point of interest, C

$T_{o\chi}$ ≡ average daily water temperature at travel time distance upstream from point of interest, C

$T_{w\chi}$ ≡ average maximum daytime water temperature (at sunset) at point of interest, C

K_d ≡ first order thermal exchange coefficient for daily conditions, $J/m^2/s$

K_χ ≡ first order thermal exchange coefficient for daytime conditions, $J/m^2/s/C$

ρ ≡ density of water = 1000 kg/m^3

c_p ≡ specific heat of water = 4182 J/kg/C

Because of the assumed symmetry in daytime and nighttime temperature fluctuations, it is only necessary to calculate the difference between the maximum daytime and average daily water temperatures to obtain the minimum water temperature.

$$T_{wn} = T_{wd} - (T_{w\chi} - T_{wd}) \tag{28}$$

where T_{wn} ≡ average minimum nighttime water temperature (at sunrise) at point of interest, C

$T_{w\chi}$ ≡ average maximum daytime water temperature (at sunset) at point of interest, C

T_{wd} ≡ average daily water temperature (at solar noon) at point of interest, C

Validation

The regression models for the validation gauges were used for comparison to the heat transport model (Theurer and Voos 1982a). Table 1 gives the mean difference (Δ) and probable difference range (δ) before calibration, by months, for the years 1964 to 1979. Table 2 gives the same statistics for "normal" discharges and meteorological conditions. The probable difference range is the 50 percent confidence limits about the mean difference; that is, 50 percent of the data from the validation gauge regression model will fall within Δ ± δ of the transport model.

Care must be taken not to assume that the differences represent errors. Where there is a difference, it can only be said that both temperatures cannot be correct. Errors do exist in both the regression and transport models. It has been pointed out that the published water temperature data does not necessarily represent the average daily water temperatures (Theurer and Voos 1982a). Therefore, it can only be expected that the regression model predictions generally fall within the minimum/maximum daily water temperatures.

SUMMARY AND CONCLUSION

The heat transport equation is transformed to a closed form equation by use of a Taylor series approximation for the heat flux. The resulting analytic expression is easily solved to determine the average daily water temperatures and the diurnal fluctuations. A steady flow assumption was necessary for each solution; however, the diurnal fluctuation solution permits estimates of the 24-hour temperature variation about the average daily.

The heat transport solution is probably the most accurate component of the instream water temperature model. More error between predicted and actual water temperatures probably can be attributed to the heat flux relationships and input estimation for the hydrology, meteorology, and stream geometry than to the one-dimensional, steady flow, non-dispersed assumptions inherent in the transport equation. However, there can be situations where the water is not mixing sufficiently for the equation to be valid; for example, very slow velocities may not force the necessary vertical and transverse mixing, or eddy currents and backwater areas will not be a part of the main flow. Such situations would require special analysis.

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Table 1.--Heat transport model statistics: 1964-1979[1]

		Jensen	Green River	State Line	Cisco	UT163
January	Δ	0.78	0.21	-0.04	0.05	-0.60
	δ	±0.57	±0.41	±0.29	±0.11	±0.51
February	Δ	0.44	0.27	-0.16	-0.04	-0.31
	δ	±0.59	±0.51	±0.57	±0.54	±0.92
March	Δ	0.70	0.46	0.21	-0.08	0.30
	δ	±0.59	0.37	±0.51	±0.35	±0.53
April	Δ	0.10	0.19	-0.13	-0.10	0.82
	δ	±0.74	±0.37	±0.90	±0.68	±0.54
May	Δ	-1.96	-1.01	0.00	0.39	-0.73
	δ	±0.91	±0.57	±0.49	±0.48	±0.78
June	Δ	-1.46	-1.48	-0.55	-0.11	-1.77
	δ	±0.80	±0.57	±0.43	±0.41	±0.94
July	Δ	0.12	-1.78	-0.74	-0.35	-1.23
	δ	±1.03	±0.52	±0.53	±0.55	±0.66
August	Δ	-0.26	-1.67	-0.66	-0.56	-0.75
	δ	±0.94	±0.32	±0.41	±0.52	±0.63
September	Δ	-0.01	-0.97	-0.58	-0.70	-1.03
	δ	±0.80	±0.38	±0.68	±0.63	±0.62
October	Δ	-0.13	-0.91	-0.28	-0.72	-0.79
	δ	±0.47	±0.45	±0.38	±0.51	±1.03
November	Δ	0.06	-0.90	-0.86	-1.17	-1.84
	δ	±0.53	±0.34	±0.37	±0.44	±0.78
December	Δ	0.76	-0.21	-1.03	-0.97	-2.64
	δ	±0.71	±0.36	±0.35	±0.35	±0.86
Annual	Δ	-0.08	-0.65	-0.40	-0.35	-0.84
	δ	±0.91	±0.67	±0.56	±0.55	±0.92

[1]After Theurer and Voos (1982a).

Table 2.--Heat transport model statistics: normals[1]

		Jensen	Green River	State Line	Cisco	UT163
January	Δ	1.11	0.00	0.27	0.25	-0.88
February	Δ	0.76	0.52	0.02	-0.14	-1.01
March	Δ	0.92	0.65	0.25	-0.10	-0.03
April	Δ	0.61	0.39	0.18	0.11	0.45
May	Δ	-1.19	-0.49	0.15	0.63	-0.46
June	Δ	-1.36	-1.24	-0.13	0.55	-1.63
July	Δ	0.52	-1.49	-0.26	-0.70	-0.49
August	Δ	0.52	-1.49	-0.26	-0.70	-0.49
September	Δ	0.36	-1.13	-0.64	-1.03	-1.50
October	Δ	0.17	-0.71	-0.32	-0.99	-1.85
November	Δ	-0.10	-1.07	-0.96	-1.46	-2.64
December	Δ	0.54	-0.65	-1.11	-1.26	-3.38
Annual	Δ	0.24	-0.56	-0.23	-0.33	-1.21
	δ	±0.53	±0.53	±0.31	±0.49	±0.73

[1]After Theurer and Voos (1982a).

ARS VIEW - SUBSURFACE FLOW MODELING

C. R. Amerman[1]

The term "model" means something a little different to each of those who use it. To many, a model is a prediction tool. To others, a model is an expression of our best current understanding of the modeled phenomenon. Many ARS scientists studying various aspects of subsurface flow use models as a means of summarizing our current understanding for purposes of pinpointing voids in that understanding, or for purposes of transferring technology to others. Another use of models in research is that of assessing the sensitivity of a system output to one or more of several physical inputs, system properties, or system conditions. In the case of subsurface waters, we have a system that cannot be directly observed in the macroscale. Deterministic or physical models, as proxies for the real systems, provide for a degree of experimentation into physical processes, that is, a means of improving concepts and qualitative, if not quantitative, understanding.

Several conceptually different approaches to modeling may be taken, as has been discussed the last several days. Within ARS, the primary approach to subsurface flow modeling has been deterministic. This is probably partly because soil physicists, soil mechanicists, and geohydrologists already had a highly developed subsurface flow theory in the early 1960's, when surface-water hydrologists in ARS and elsewhere developed a new appreciation for the continuum nature of surface and subsurface waters. Soil physicists at the time already had demonstrated the usefulness of deterministic methods (finite difference modeling of the Richards' equation, for example) for the determination of infiltration and postinfiltration redistribution of water. Ground-water hydrologists were routinely using the Laplace equation, as well as various physically derived methods of modeling flow in saturated materials.

Almost coincident with the recognition by traditional hydrologists of the role of subsurface flow in the surface manifestation of the hydrologic cycle was recognition of the importance to society of various substances being carried and distributed around the landscape by flowing water. The distribution of these materials (for example, solutes, sediments) is an important reason why little effort has yet been made to approach subsurface flow from other than a deterministic standpoint. To our knowledge at this time, deterministic models provide the only viable mathematical approach to describing flow and transport processes in the landscape.

Since the early 1960's, ARS and other hydrologists have applied various models based on the laws of motion, continuity, and conservation to questions of infiltration, drainage, groundwater movement, and evapotranspiration. In common with most modeling efforts, simplified conditions, minimum dimensionality, and simplifying assumptions have characterized these efforts. Infiltration, for example, has been approached mainly as a one-dimensional, point-specific phenomenon when we know that it is always, to some extent, three-dimensional and spatially distributed.

We have also dealt in our models mainly with idealized media. Layering may take place, but we have looked upon the media within a layer as being essentially homogeneous and granular.

Given the state of our knowledge, we have had little choice but to limit consideration to idealized systems. ARS and other scientists for the past several years have been coming to grips with the idealized nature of past modeling efforts and their application in the real world. We are concerned with our inability to economically emulate three dimensionality in our models. We are concerned with the question of how to account in our modeling for spatial and temporal variability on the hydraulic properties of the media within natural flow systems.

A particularly pertinent concern to some subsurface flow researchers is whether our equations and mathematical conceptualizations represent what is really happening in natural soils and rocks. For example, we are unable at this time to mathematically describe the flow of water through macropores and such large voids as occur in fractured rocks. So, we approximate it (model it) with the same equations we use for porous media but select different values for the hydraulic properties.

The upper surface of a flow system is usually a soil surface and supports vegetation. A phenomenon that we know very little about, in the context of being able to give it mathematical expression, is that of root growth and distribution and the distributed removal of water from the flow system by roots.

Some are concerned with the complexity of the deterministic approach, the amount of field exploration and testing required to obtain the inputs necessary for this type of modeling, and the demands made upon users of these models. Some view the deterministic approach as a preliminary or interim necessity for meeting a long range goal of providing simple models to end-users. The reasoning here is that we must understand how to meaningfully and legitimately simplify the description of that system via a model.

The questions of model verification and evaluation of accuracy do not have clear, straightforward answers. As noted above, subsurface flow systems cannot be directly observed in the macroscale. Point observations, for reasons of practicality, must usually be made quite sparingly. Point observations almost always involve

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disturbance of the system one is attempting to observe, so almost inevitably influence the system in some degree. Physical (scaled down) models usually involve many of the same simplifications and assumptions as mathematical models. If one accepts the validity of Darcy's law, then observations on a sand model, for example, may reflect more on how well the sand model was assembled than on the accuracy of the Darcy-based mathematical model.

Tests for accuracy and validity, then, are often indirect or qualitative in nature. One may evaluate mathematical models for convergence and stability, or for the errors associated with numerical methods. Under certain conditions, one model may be compared against another when there is reason to believe one of them may be used as a standard. Otherwise, one must usually accept disturbances of the real system in order to make measurements; one must base tests on observations relative to the appearance of a seepage face, discharge or a spring, or timing of tracer appearance at a discharge point; or one must use some other macroscale and qualitative method.

To some I may appear to be presenting, on the part of ARS, a rather negative view of subsurface flow modeling. Our view is not negative at all. On the contrary, it is a very positive view. Advancement of our knowledge of subsurface flow processes depends upon the judicious use of a mixture of modeling and basic research into the physics of subsurface flow. Modeling, properly performed and interpreted, should assist researchers in selecting the subjects for further basic research. Subsurface flow models are probably the most efficient means of expressing what we know about that phenomenon.

Both scientists and those who wish to put models to use for nonresearch purposes, however, must keep in perspective the status of a particular model vis-a-vis the correspondence between state-of-the-art knowledge (or our mathematical ability to express it) and the real-world prototype. If a properly constructed model does not represent the real world well, the problem is probably with the current state of knowledge regarding the phenomenon being modeled or with our ability to measure that phenomenon.

Realizing that no model can be better than the current state of knowledge about the phenomenon of interest, deciding which model to choose from among several available should be based on questions asked in the context of the proposed use of the model. What simplifications were made? What assumptions were made? How do these simplifications and assumptions square with the real system and the questions about that system that are to be answered by the model? Once the issues of simplification and assumption are decided for a particular subsurface flow model, its form is usually that of a finite difference or finite element approximation to the solution of nonlinear, partial differential equations. Accuracy then depends upon the accuracy with which real-system geometry, boundary conditions, initial conditions, and media properties may be measured or approximated. Accuracy also depends upon the spatial increment scale used to approximate the geometry of the system and the size of the time steps used. The particular method of numerical approximation has a predictable influence upon the latter spatial and temporal increments, so some knowledge about numerical methods is needed for this part of the decision-making process.

As with most departments of life, there are no simple answers regarding the adequacy and/or the accuracy of subsurface flow models. If one must obtain quantitative information about a subsurface flow system and physical observation is impracticable, then a model will probably be used. Judgment and knowledge will have to be exercised in selecting the model. And the selection process may have to be exercised all over again for the next subsurface flow problem that arrives. Any model selected will only approximate a true solution. We have no good handles on the degree of approximation, because, while we can evaluate the probable error of a numerical technique, extensive field experience is required to develop a knowledge of the goodness with which we can estimate or measure the physical inputs to the model. Assuming that subsurface flow equations do indeed model the real world, uncertainties in measuring or estimating these physical inputs may well overshadow for some time to come any lack of accuracy associated with numerical approximations to the equations.

To summarize the ARS view, subsurface flow modeling has a long way to go. It is a very useful technique in the research environment. For many reasons, subsurface flow models must be used carefully for real-world prediction purposes, and those who use them should familiarize themselves with numerical methods, with the simplifications inherent in current modeling efforts, and in general, with the deficiencies in current knowledge about subsurface flow. ARS and other scientists who recognize the need for basic research on many issues associated with subsurface flow, are currently pursuing such research, and are continually seeking for better ways to push back the curtain obscuring subsurface flow physics.

A REVIEW OF SELECTED AVAILABLE SATURATED-UNSATURATED FLOW MODELS

Everett P. Springer[1]

INTRODUCTION

Solutions to porous media flow problems are important to understanding agricultural systems. Some typical problems requiring knowledge of porous media physics are land drainage, irrigation design, and pesticide application. Solutions for the most general cases require numerical techniques, either a finite difference or finite element method. The objective of this paper is to present available computer codes designed to solve the saturated-unsaturated flow problem. Three computer models representing different techniques, finite element vs. finite difference, are briefly described, and additional models are indexed in tabular form. The purpose is to alert potential users to available models so that these efforts will not be duplicated by future projects.

Lappala (1982) noted that the primary use of these models has been as a tool which furthers the understanding of the flow system. He cited five reasons why these models have not been routinely applied to field problems: (1) difficulty in developing descriptive theories that adequately describe observed phenomena, (2) inability to obtain parameters at reasonable cost, (3) insufficient knowledge of scale dependence and spatial variability of parameters and/or state variables, (4) the coupled transport of multiple species and/or mass and energy for transport problems is very complex, and (5) the lack of field data to calibrate these models. Despite these difficulties, there have been some field applications of these types of models (i.e., Nelson et al. 1983, and Segol 1982).

BACKGROUND

The general partial differential equation for variably saturated flow, including source/sink terms, compressible storage in the saturated zone, and isothermal flow is (Lappala 1982)

$$\frac{\partial(\rho S\phi)}{\partial t} + \frac{\partial}{\partial \underset{\sim}{X}}\left[\frac{\rho^2 g\bar{K}}{\mu} K_r \frac{\partial H}{\partial \underset{\sim}{X}}\right] + Q = 0 \qquad (1)$$

where ρ = $(\underset{\sim}{X},t,P)$ = fluid density, ML^{-3}, in which P is fluid pressure,

$S = S(\underset{\sim}{X},t,P)$ = saturation,

ϕ = $(\underset{\sim}{X},t,P)$ = porosity,

K = intrinsic permeability, L^2,

g = gravitational acceleration, LT^{-2},

μ = dynmamic fluid viscosity, $ML^{-1}T^{-1}$,

H = total potential, L, for fluid of density, sum of hydrostatic, gravitational, capillary, and osmotic,

$Q = Q(\underset{\sim}{X},H)$ = source/sink term, $ML^{-3}T^{-1}$,

$K_r = K_r(X_i,t,S)$ = relative hydraulic conductivity,

t = time, T,

and $\underset{\sim}{X}$ = spatial coordinate, i = 1,2,3,L.

Analytical solutions are available for equation 1, but they do not include the source/sink term. Lappala (1982) indicated that for analytical solution the dependence of relative conductivity on pressure potential is limited to simple functional forms; the heterogeneity is a simple function of the space coordinates; and in multidimensional problems, the geometry is restricted.

Solution of equation 1 for complex field situations requires numerical methods. These algorithms use either a finite difference or a finite element technique applied directly to equation 1 or to a transformation of equation 1. In solving problems of flow in saturated-unsaturated regions, equation 1 is formulated in terms of potential. The diffusivity formulation is inappropriate because volumetric water content is not the state variable used to describe flow in saturated systems. The same rationale is applied to the matric flux potential or Kirchoff transformation equation.

NUMERICAL MODELS

Three existing models (computer codes) that are available to solve flow problems in saturated-unsaturated regions are reviewed.

UNSAT2

Description

Documentation for UNSAT2 can be found in Neuman et al. (1974, 1975) and Feddes et al. (1975). The model is capable of solving for flow in two-dimensional vertical or horizontal regions, or three-dimensional axisymmetric flow to a well. The equation solved is a simplified form of equation 1, not including osmotic or solute potential, fluid density-pressure relationships, and/or compressibility of the saturated zone. Therefore, equation 1 becomes

$$\frac{\partial}{\partial \underset{\sim}{X}}\left[KrKs_{ij}\frac{\partial P}{\partial \underset{\sim}{X}} + Kr(P)Ks_{ij}\right] + C(P)\frac{\partial P}{\partial t} + Q = 0 \qquad (2)$$

where $\underset{\sim}{X}$ = two-dimensional spatial coordinates, L,

K^s_{ij} = saturated conductivity tensor, LT^{-1},

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$C(P)$ = specific moisture capacity, L^{-1},

and all others are as defined in equation 1.

UNSAT2 uses the Galerkin finite element method for solution of the spatial domain and has an option for either a centered or backward finite differencing technique for time step solutions. Linear triangular elements are used to discretize the spatial domain. Figure 1 presents a mesh for UNSAT2. The reader may note that rectangles rather than triangles are used for the majority of the flow region. The computer program will construct triangles out of a rectangular element, and triangular elements that are entered are handled differently from the rectangular elements.

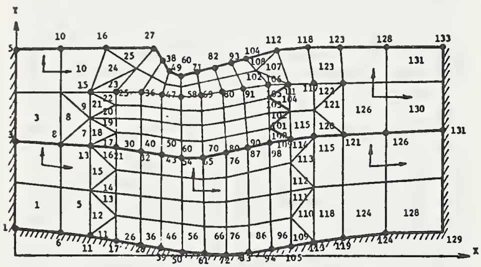

Figure 1.--Finite element mesh for UNSAT2 (from Neuman et al. 1974)

UNSAT2 has some very desirable features for simulation of agricultural flow systems. It can determine the flux given a potential upper boundary flux for either evaporation or infiltration. If the conditions of surface ponding in the case of infiltration arises, the upper boundary will become a constant head boundary. Seepage faces are allowed, which is particularly useful for hillslope hydrology problems. A major feature attractive to agricultural applications, and not included in most other models of this type, is plant root extraction of water, given an applied potential transpiration and soil water potential status. The sink term, Q, in equations 1 and 2 is defined by Neuman et al. (1974) as

$$Q = K^{s}_{11} K_r(P)\ (P-P_r)b' \qquad (3)$$

where K^{s}_{11} = saturated hydraulic conductivity parallel to the horizontal axis, LT^{-1},

P = soil water pressure potential, L,

P_r = pressure potential to the root, L

and b' = empirical quantity defined as the root effectiveness function L^{-2}.

Values are assigned to b' throughout the rooting depth. Plant growth can be simulated by increasing the values of b' with depth as the growing season progresses. Since the model does not consider solute transport, this could be a limitation in applying UNSAT2 to highly saline soils. UNSAT2 can accommodate anisotropy in the saturated hydraulic conductivity, vertical layering, and heterogeneity within the flow field.

Input Requirements

Solutions to equations for unsaturated porous media flow, whether analytic or numerical, require the relationships between pressure potential, moisture content, and relative conductivity. These relationships are required for each material in the system, and if a heterogeneous field is being modeled, the number of curves entered can be substantial. UNSAT2 uses a table look-up procedure and linear interpolation to determine values of volumetric water content and relative conductivity.

Anisotropy is entered through the saturated conductivity values for the coordinate directions. If the primary direction of permeability is not parallel to the coordinate axes, an angle of the direction of primary permeability can be entered.

Geometric data required includes location of seepage faces, different materials (layers), wells, and plants. Each element (fig. 1) is assigned a material number which introduces heterogeneity or layering.

Plant transpiration uses data for each plant species. For a species, the inputs are maximum rooting depth in terms of nodes, wilting point pressure potential, and values for the root effectiveness function (b') for each node within the root zone. From figure 2, it can be seen that the width of the root zone (W_{i-1}, W_i) is half the distance between adjacent transverse lines. Extraction is uniform within this horizontal distance, but extraction can vary between nodal columns.

TRUST

Description

TRUST was developed as a tool for simulating variably saturated flow in multidimensional, deforming regions (Narasimhan and Witherspoon 1976, 1977, 1978; Narasimhan et al. 1978; Reisenauer et al. 1982). TRUST uses the integrated finite difference method (IFDM) to solve

$$Q + \int_{\Gamma} \rho_w \frac{K \rho_w g}{\mu} \nabla(Z+P)\ \vec{n} d\Gamma = \frac{d}{dP}(\rho_w V n S) \frac{\partial P}{\partial t} \qquad (4)$$

where Γ = the surface boundary of finite region,

P_w = density of water, ML^{-3},

V = volume of the region,

and all others are defined in equation 1.

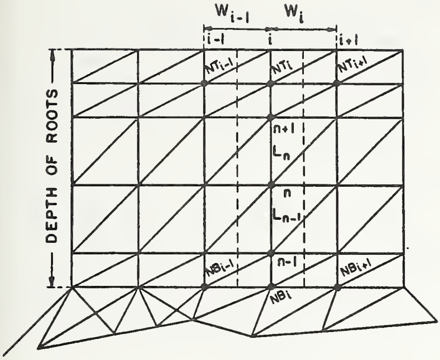

Figure 2.--Root extraction geometry for UNSAT2 (from Neuman et al. 1974)

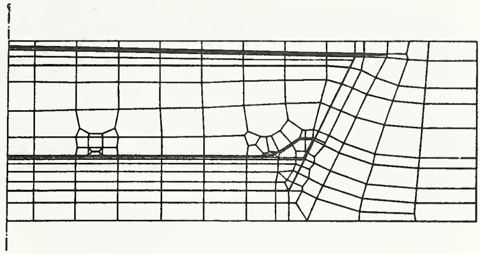

Figure 3.--Mesh for TRUST solution (from Nelson et al. 1983).

The IFDM requires the spatial domain to be discretized into elements or cells associated with each node (fig. 3). Figure 4 shows a single cell and its node with adjacent nodes. The algorithm balances the flux calculations between adjacent nodes, and the boundary between these nodes (Γ, ℓ, m in fig. 4) should be orthogonal or nearly orthogonal. Therefore, mesh construction for this program can be quite difficult, particularly for three-dimensional problems.

Reisenauer et al. (1982) provided a list of problems that have utilized TRUST. The following is a partial list: (1) settlement and consolidation in soft-clay systems under different loads; (2) infiltration and drainage in variably saturated columns, ditches and sand boxes; and (3) analysis of slug test, constant rate injection and drawdown well test in media with single or multiple fractures. Agricultural applications are nonexistent, but TRUST may have potential for the tillage reconsolidation problem.

Input Requirements

From equation 4, it can be seen that the physical parameters are in what is termed their "primitive" form. The model requires both fluid and media properties. Media properties include the pressure potential versus saturation and relative permeability. The user can enter either a table of values, or the parameters for the functional form of these relationships. Hysteresis can be incorporated in both relationships. Fluid properties required include viscosity, compressibility, and density.

As already noted, geometric inputs can be extensive. For two-dimensional problems, Foote et al. (1982) have developed an interactive, graphics-based computer code known as DIGRD.

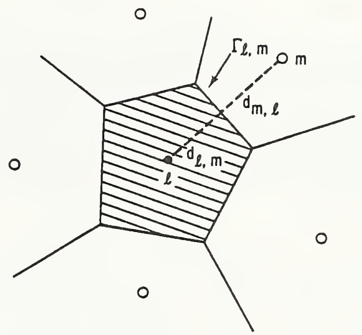

Figure 4.--Element associated with nodal point, ℓ , for integrated finite difference scheme used in TRUST (from Reisenauer et al. 1982).

FREEZE

Description

The final model to be discussed was reported by Freeze (1971). The model uses finite differences to solve equation 1, and it can consider heterogeneity, anisotropy, and compressibility in the saturated zone for three-dimensional regions. It has been used by Freeze (1971, 1972a and b) to study regional aquifers and watershed response, while a two-dimensional version was used by Stephenson and Freeze (1974) to investigate snowmelt contribution to runoff on a vertical cross section within the Reynolds Creek Watershed.

Input Requirements

FREEZE will handle heterogeneity and anisotropy throughout the entire flow domain, as well as hysteresis in the unsaturated zone and compressibility in the saturated zone. The

relationships between pressure potential, water content, and relative conductivity are entered in tabular form and intermediate values are found via linear interpolation. Anisotropy is considered in the direction of the principal coordinates.

Internal sources/sinks are treated. Boundary conditions include the constant pressure potential or flux, seepage face, or time variable upper boundary.

ADDITIONAL MODELS

Table 1 taken from Oster (1982) is a compilation of models which were developed to model saturated-unsaturated porous media flow. It should be noted that several of these codes consider transport as well as flow.

CONCLUSIONS

As was previously stated, this review is intended to alert potential users as to the computer models available which solve for saturated-unsaturated flow in porous media. It was not my intention to compare the different algorithms. Personal preferences, particulary user familiarity with either finite differences or finite elements, will dictate the algorithm utilized. Of course, the particular problem will dictate what features will be included.

Everyday field application of these models is still some time in the future. Segol (1982) presented a case study of a field application of a model similar to UNSAT2. The results indicated field application was possible, but the model could not be used in a straightforward manner. Considerable insight of porus media flow physics and numerical methods is required, particularly in relation to mesh construction to provide adequate solutions.

The conceptual basis of these models forces one to look at the subsurface flow systems in terms of their basic parameters and state variables. Utilization of these models in sensitivity analyses may provide more insight in data network design. Using these algorithms as prototypes, further understanding of porous media flow in agricultural systems can be attained and used in management.

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Table 1.--Summary of flow codes (from Oster 1982)

Code Name	Dimensions 1	Dimensions 2	Dimensions 3	Discretization method FDM	IFDM	FEM	Special features	Past applications	Principal Contact	Comments
AMOCO			X	X				Oil reservior	AMOCO	Proprietary Code
ALPURS			X	X			Three-phase oil water, gas		Mobil Corp.	Proprietary Code
BETA-II			X	X				Oil reservoir	Intercomp.	Proprietary Code
BRUTSAERT1		X		X				Experimental	Brutsaert	
BRUTSAERT2		X		X				Experimental/ Laboratory	Brutsaert	
CMG			X	X				Oil reservoir	CMG	Proprietary Code
COOK		X					Two-phase oil & gas	Oil reservoir	Cook	Proprietary Code
DELAAT		X				X	Roots, evapo-transpiration	Groundwater extraction crop production	De Laat	European Code
FEMWATER		X				X			Yeh	
FLUMP		X				X			Narasimhan	
GRANDALF		X		X				Underground nuclear explosions	Morrison	
GPSIM			X	X					Exxon	Proprietary Code
MOMOLS	X			X				Experimental	Rojstoczer	
PORES			X	X				Oil reservoir	UKAEA	European Code
REEVES-DUGUID		X				X	Radioactive decay		Reeves	
SHELL			X	X				Oil reservoir	Shell Oil Co.	Proprietary Code
SSC			X					Oil reservoir	SSC	Proprietary Code
SUM2		X				X	Roots, evapo-transpiration	Groundwater extraction	De Laat	European Code
SUPERMOCK		X		X			Roots	Groundwater extraction	Reed	
TRACR3D			X	X			1- or 2-phase flow with tracer in either phase (air or water) Freundlich, Langmuir sorption, radioactive decay, capillary effects	Tracer flow in unsat. conditions, radionuclude transport, tracer flow in fractured system	Travis	Can operate in 1, 2 or 3 dimensions
TRIPM		X				X	3-member decay chain	Radioactive waste disposal	Gureghian	
TRUST			X		X				Narasimham	
TS&E			X					Oil reservoir	Tech. Soft. & Eng.	Proprietary Code
UNFLOW		X				X		Radioactive waste disposal	Pickens	
UNSAT1	X					X			van Genuchten	
UNSAT1D	X			X			Roots, evapo-transpiration	Crop studies	Bond	
UNSAT2		X				X	Roots	Engineering design	Neuman	
VERGE			X			X		Radioactive waste storage	Verge	
VS2D		X		X			Roots, evapo-transpiration		Lappala	
WAFE		X		X			Coupled heat & 2-phase mass transport (air vapor & liquid). Accurate treatment of H_2O separate velocity field phase	Confined under-ground radioactive waste disposal, in-situ fossil energy recovery studies, 2-phase flow and tracer studies	Travis	Can operate in 1 or 2 dimensions

Key: FDM = finite differene method;
IFDM = integrated finite difference method; and
FEM = finite element method.

EVAPOTRANSPIRATION MODELS: AN OVERVIEW [1/]

J. L. Hatfield [2/]

INTRODUCTION

Evapotranspiration represents the total water loss by a surface and is the combination of evaporation from the soil surface and evaporation from plant surfaces of water transported from the soil volume. This process is an important part of the hydrologic cycle because it couples stored soil water with the atmosphere. As an energy exchange process, evapotranspiration also includes the energy consumed in evaporating free water; in other words, intercepted precipitation or dew, from plant surfaces.

There are many available evapotranspiration models in the literature. However, before we select one to use in any application, we should answer three basic questions: (1) what temporal scale is necessary for data input; (2) what spatial scale is valid in the model; and (3) what input accuracy is necessary for the model? In selecting a crop or hydrologic model, it appears that researchers have often ignored these questions. However, it may not always be possible to answer completely before the selection, because the models may not have been evaluated over conditions for which the user wishes to apply them. These conditions may range from large areas with multiple crops to undulating terrain with a mixture of species; for example, rangeland or forests. In this overview, I shall examine some of the current models and their limitations.

LIMITATIONS TO EVAPOTRANSPIRATION

As a physical process, evapotranspiration is subject to four limitations. These are (1) solar energy available, net radiation to the surface; (2) gradients of energy exchange; for example, wind, water vapor, and temperature; (3) soil water availability; and (4) the plant, which exerts control over the water flow from the soil to the atmosphere.

Briefly, net radiation is the solar energy input into the surface and is the net balance of the incoming and reflected shortwave radiation and the incoming and emitted longwave radiation. The flux gradients quantify the exchange rates of water vapor, momentum (wind), and sensible heat (temperature gradients) and determine the direction (for example, to or from the surface) of the energy exchange. Soil water availability represents the availability of the resource (water) to be consumed by the available energy (net radiation) and transported into the atmosphere (flux gradients) and is influenced by the physical properties of the soil. The plant can be considered as a conducting and a dissipating mechanism through its extensive system of roots (conductors) and leaves (dissipators). A plant offers some resistance to water flow at all steps which must be considered in a realistic evapotranspiration model.

The term "potential evapotranspiration" is often used to describe the amount of water lost, considering only radiation and energy gradients. However, there are differences of opinion on what potential evapotranspiration really means, because some individuals treat it as a crop-specific value while others use it in a more general sense. Others prefer to use reference evapotranspiration as a more representative description, because it allows for a closer alliance between the aerodynamic properties of the crop being measured and some reference; for example, alfalfa.

It is necessary to point out that of the 20 methods listed by Jensen (1973) for calculating potential evapotranspiration, most contain empirical coefficients which are empirically derived for a given set of conditions. A user should examine a method for its limitations before applying it to a situation far removed from the initial conditions. The user should also realize that most of the techniques have not been extensively tested; rather, they have been evaluated on limited data sets. In essence, the user should be aware of possible limitations by critically examining the model and its empirical coefficients.

Given the four constraints on evapotranspiration, it is necessary to adjust any potential evapotranspiration to the actual amount of evapotranspiration by considering the available soil water and the crop. This requires a thorough understanding of the available soil water, rooting depth, and the relationships between evapotranspiration and soil water for the particular soil and crop. The latter aspect involves the restrictions which a plant places on water flow through stomatal or canopy resistance (Van Bavel and Ahmed 1976). These aspects must be considered in all applications of evapotranspiration models.

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EVAPOTRANSPIRATION MODELS

In this overview, only the currently used evapotranspiration models will be discussed. These represent the vast majority of applications, as evidenced by a survey of the literature involving evapotranspiration models. A summary of these models is given in table 1. Jensen (1973) presents a more thorough evaluation of these models and discusses their limitations. The reader is referred to his treatise for a more complete description. It should be realized that all of these models may only be applicable to the areas and crops for which they have been calibrated. All evapotranspiration models should be used with caution.

If all available models are suspect, then what is available for use in the current modeling efforts and validation studies? In reality, we have two distinct questions, because of the constraint on inputs available to drive models and of the need for a validation technique to be somewhat independent of the technique under evaluation. For validation studies we could consider techniques, such as the surface energy balance, eddy correlation, Bowen ratio, flux profile methods, or lysimeters, for providing a set of test data; however, it is beyond comprehension that the necessary inputs would be available to drive these methods in our current data bases. Therefore, we will be designing validation studies using methodologies that differ from those for our application model. It will be necessary to utilize a lysimeter as a standard reference in these studies.

To fully understand where some of the differences are in these models, let us examine two models in detail and discuss how they may be utilized. The first one is the Penman-Monteith model as proposed by Monteith (1965) and given as

$$LE = \frac{\Delta(R_n + G) + [\rho Cp\ (e_s(T_a) - e_a)]/r_a + r_c}{\Delta + \gamma} \quad (1)$$

where LE is the latent heat of vaporization (W/m^2), Δ the slope of the saturation vapor pressure curve (kPa/C), R_N net radiation (W/m^2), $\rho\ C_p$ the volumetric heat capacity of air, ($J/kg/C^{-1}$), $e_s\ (T_a)$ the saturation vapor pressure at air temperature (kPa), e_a the actual vapor pressure of the air (kPa), r_a the aerodynamic resistance of the surface to water vapor transfer (s/m), the psychrometric constant (kPa/C), and r_c the canopy resistance (s/m). To estimate potential evapotranspiration, the canopy resistance is set to zero, thus forcing the crop canopy to exert no influence on the flow of water. Hatfield (1984) has found that wheat canopies have a finite resistance even under well-watered conditions (fig. 1). Van Bavel (1967) and Szeicz and Long (1969) also found that canopies under well-watered

Table 1.--Evapotranspiration models currently used in soil water balance, hydologic, and crop growth applications

Model	Input 1/	Temporal frequency of inputs	Empirical representative
Thornthwaite	T_a,N	Monthly	heat index
Blaney-Criddle	T_a,N	Monthly	temperature function
Jensen-Haise	T_a,Rs	Five Days	temperature coefficients derived from warmest months, (July)
Penman-Monteith	T_a,R_N,G, u, e_a	Daily	wind function to represent aerodynamics resistance
van Bavel-Businger	T_a,R_N,G,u,P,e_a,z,z_o	Daily	roughness height as a function of crop height
Ritchie	T_a,R_N,G,u,e_a	Daily	soil evaporation as a function of ground cover
Surface Energy	T_a,R_s,R_N,G,r_a	Minute	estimation of r_a via stability formulas extension to complete days

1/ T_a - temperature, air
N - daylight hours
R_s - solar radiation
R_N - net radiation
G - soil heaf flux
u - windspeed
e_a - actual vapor pressure
P - pressure
z_o - roughness height
z - height of measurement
T_s - surface temperature
r_a - aerodynamic resistance

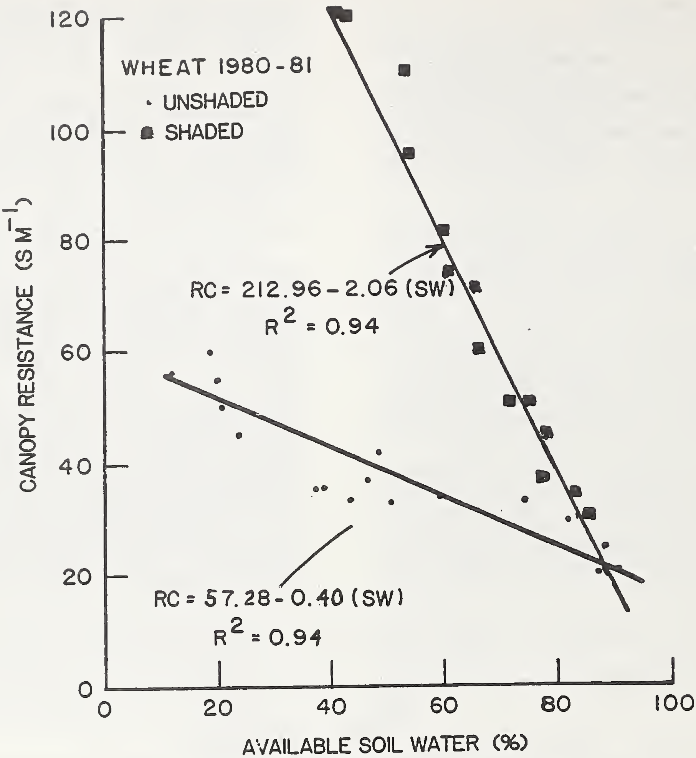

Figure 1.--Changes in canopy resistance of wheat under shaded and unshaded conditions to soil water availability.

conditions have a measurable canopy resistance. Also, in application, many individuals use the wind function term in Equation 1 as (1 + 0.0061u) with windspeed measured at 2 m above the soil surface. If we expand the r_a term as the log-law representation given as

$$r_a = \frac{(\ln (z - d)/z_o)^2}{k^2 u} \qquad (2)$$

where z is the height of measurement (m), d is the displacement height (m), z_o the roughness height (m), and k the von Karman's constant (0.40), then we can immediately begin to see a limitation of this windspeed function. Since the roughness height of a surface varies with the height, foliage density, and windspeed, it is apparent that the windspeed function would not remain constant throughout the growth of a crop. It is suggested that, if the Penman-Monteith equation is to be used, the aerodynamic resistance with stability corrections be employed as a more appropriate means of obtaining the r_a term (Van Bavel and Hillel 1976, Hatfield et al. 1983). If the model is to be used in the estimation of actual evapotranspiration, then the r_c term must be included to provide for a better representation of crop response to soil water conditions. This latter aspect still needs detailed research before being applicable to a wide variety of crops.

Ritchie (1972) presented a method for separating soil evaporation from crop transpiration which incorporates empirical values for soil albedo, net radiation, and solar radiation available at the soil surface as a function of leaf area index (LAI). The empirical coefficients were fit to a variety of crops and may cause some error when applied to conditions outside of the original data set, as would be appropriate with any empirical equation. This model does provide a fundamental framework for estimating soil evaporation, which is often necessary in detailed simulation models. Another model which may be applicable to large areas would be the surface energy balance model given as

$$LE = R_n + G - \rho Cp\ (T_s - T_a)/r_a \quad (3)$$

where T_s is the surface temperature (^oC). This representation provides a direct input of the canopy into the model; and Hatfield et al. (1983) have discussed several limitations, while Hatfield et al. (1984a) have shown its utility for a wide variety of surfaces. One advantage of this method is that an estimate of actual evapotranspiration is obtained from the model. This would be applicable to large areas and would be extremely useful for rangeland or covering complete watersheds. Hatfield et al. (1984b) have shown good agreement between estimated and measured soil water extraction in undulating topography with this method (fig. 2). This method estimates an instantaneous evapotranspiration, and to be useful this needs to be extrapolated to a daily total or several temporal inputs are needed to provide a complete integration over an entire 24-hour period. Jackson et al. (1983) provide a possible method for obtaining daily totals for instantaneous measurements. This technique is still in the research phase but may provide a valuable tool for estimating actual evapotranspiration in large areas of range or crop land where a spatial average over several hectares will be appropriate in the validation study.

NEEDED RESEARCH

Evapotranspiration is a dynamic term which is a function of the limitations discussed earlier. This is best shown with the autocorrelation function shown in figure 3 for evaporation from a bare soil in a lysimeter at Davis, CA. It is striking how rapidly the correlation between days disappears, and after 2 days soil evaporation can be considered to be independent from that of the previous days. Thus, we need models which are driven by daily inputs if we are to realistically estimate evapotranspiration.

If evapotranspiration models are to be applied as an integral part of larger crop growth, erosion, or watershed models, then appropriate large scale evapotranspiration models need to be utilized. We probably have the models available now in the Penman-Monteith or surface energy balance form, but these need to be tested over large fields or range sites and undulating topography. If additional atmospheric and crop inputs are needed to drive these models, then these need to be identified as soon as possible in order for data collection to begin. Evaluation of these models will have to be conducted over the spatial scale which they will be applied. Saxton et al. (1974) have shown that it is possible to use the combination equation proposed by Van Bavel (1966) to estimate watershed evapotranspiration. They did not, however, compare their results to actual evapotranspiration which remains to be done for large areas in a comprehensive manner.

The application of evapotranspiration models should consider a variety of users, all with different requirements, and the models will have to accommodate their needs. However, continued interaction between users will help to ensure that these needs are met.

Evapotranspiration research faces a challenge to develop more accurate models which estimate actual evapotranspiration over large areas. This means we must expand past research to cover an entire growing season with multiple crops over large areas and perennial agriculture and rangeland situations. These are not beyond our grasp but require a thorough yet broad outlook of the agricultural system. By doing so, we will improve our understanding of the dynamics of the soil-plant-atmosphere system from which we can begin to make inferences as to management impacts and species response to management.

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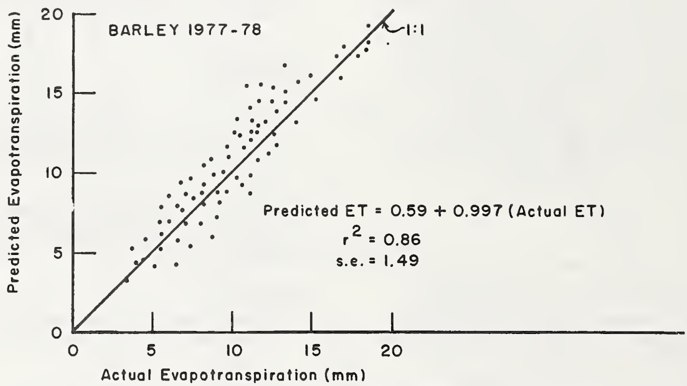

Figure 2.--Comparison of predicted daily evapotranspiration in barley to the actual daily wateruse in undulating terrain.

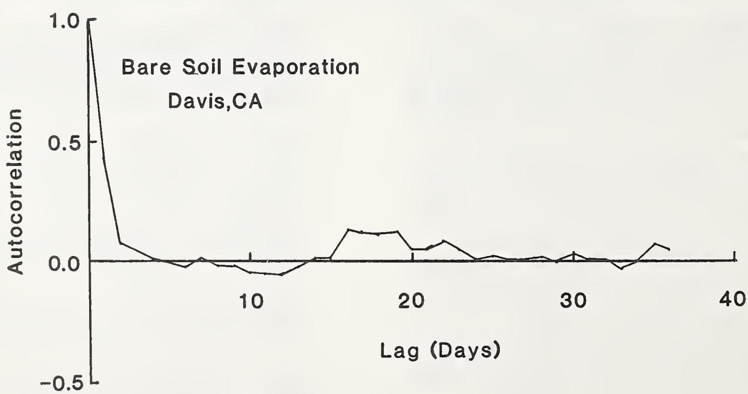

Figure 3.--Autocorrelation function of bare soil evaporation at Davis, CA.

DRAINMOD, A WATER MANAGEMENT MODEL FOR ARTIFICIALLY DRAINED SOILS

R. W. Skaggs[1]

INTRODUCTION

DRAINMOD is a computer simulation model for high water table soils that are artificially drained. It was developed for use in design and evaluation of water management systems which may include various combinations of surface and subsurface components. The model can be used to predict the response of the water table and the soil water regime above it to rainfall, evapotranspiration (ET), given degrees of surface and subsurface drainage, and the use of water table control or subirrigation practices. Irrigation applied to the surface can also be considered and the model has been used to determine hydraulic loading capacities of sites for land disposal of wastewater. Climatological data are used in the model to simulate the performance of a given water management system over several years of record. In this way, water management systems can be designed on a probabilistic basis as initially proposed for subsurface drainage by Van Schilfgaarde (1965) and subsequently used by Young and Ligon (1972) and Wiser et al. (1974).

The first version of DRAINMOD was written in the early 1970's (Skaggs 1975). Results of further developments including field experiments to test the validity of the model were given by Skaggs (1976, 1980, 1982) and Skaggs et al. (1981). The model has been installed on the SCS computer and is being used for design and evaluation of drainage and subirrigation systems in humid regions. The purpose of this paper is to briefly describe DRAINMOD, the assumptions on which it is based and its intended application.

MODEL DEVELOPMENT

A schematic of the type of water management system considered is given in figure 1. The soil is nearly flat and has an impermeable layer at a relatively shallow depth. Subsurface drainage is provided by drain tubes or parallel ditches at a distance, d, above the impermeable layer and spaced a distance, L, apart.

When the water level is raised in the drainage ditches, for purposes of supplying water to the root zone of the crop, the drainage rate will be reduced and water may move from the drains into the soil profile giving the shape shown by the broken curve in figure 1.

Two important criteria were adopted at the outset of the model development process. First, the model should be capable of describing water movement and storage in the profile so as to characterize the soil water regime and drainage rates with time. And second, the model should be developed such that the computer time necessary to simulate long term processes is not prohibitive. The movement of water in soil is a complex process and it would have been an easy matter to become so involved with getting exact solutions to every possible situation that the final answer would have never be obtained. The guiding principle in the model development was therefore to assemble the linkages between various components of the system and allowing the specifics to be incorporated as subroutines so that they may readily be modified when better methods are developed.

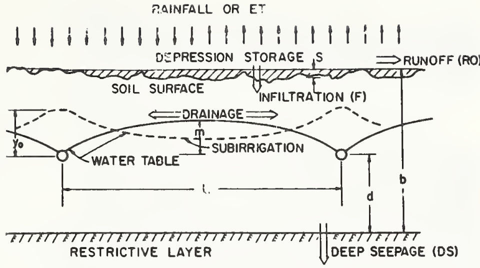

Figure 1. Schematic of water management system with subsurface drains that may be used for drainage or subirrigation.

The rates of infiltration, drainage, and evapotranspiration, and the distribution of soil water in the profile can be computed by obtaining numerical solutions to nonlinear differential equations (Freeze 1971). However, these methods would require prohibitive amounts of computer time for long term simulations and thus could not be used in the model. Instead, approximate methods were used to characterize the water movement processes.

The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between adjacent drains (fig. 1). The water balance for a time increment of t may be expressed as

$$\Delta V_a = D + ET + DS - F \qquad (1)$$

where ΔV_a is the change in the air volume or water free pore space (cm) in the section, D is drainage (cm) from (or subirrigation into) the section, ET is evapotranspiration (cm), DS is deep seepage (cm) and F is infiltration (cm), entering the section in Δt.

The terms on the right-hand side of equation 1 are computed in terms of the water table elevation, soil water content, soil properties, site and drainage system parameters, crop and stage of growth, and atmospheric conditions. The

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amount of runoff and storage on the surface is computed from a water balance at the soil surface for each time increment, which may be written as

$$P = F + \Delta S + RO \qquad (2)$$

where P is the precipitation (cm), F is infiltration (cm), ΔS is the change in volume of water stored on the surface (cm), and RO is runoff (cm) during time Δt. The basic time increment used in equations 1 and 2 is 1 hour. However when rainfall does not occur and drainage and ET rates are slow such that the water table position moves slowly with time, equation 1 is based on t of 1 day. Conversely, time increments of 0.1 h. or less are used to compute F when rainfall rates exceed the infiltration capacity.

MODEL COMPONENTS

Precipitation

Precipitation inputs to the model are hourly data which are stored and automatically accessed from the HISARS data base (Wiser 1975). Although any time distribution could be used, the rainfall rate is assumed to be uniformly distributed within each hour.

Infiltration

Infiltration of water at the soil surface is a complex process which has been studied extensively during the past two decades (Skaggs and Khaleel, 1982). Approximate methods for predicting infiltration have been proposed by Green and Ampt (1911), Horton (1939), Philip (1957), Smith (1972) and Smith and Parlange (1978), among others. The Green-Ampt equation was selected for use in this model. It was originally derived for deep homogeneous profiles with a uniform initial water content. The equation may be written as

$$f = K_s + K_s M_d S_f/F \qquad (3)$$

where f is the infiltration rate, F is accumulative infiltration, K_s is the hydraulic conductivity of the transmission zone, M_d is the fillable porosity ($M_d = \theta_s - \theta_i$), and S_f is the effective suction at the wetting front. For a given soil with a given initial water content, equation 3 may be written as

$$f = A/F + B \qquad (4)$$

where A and B are parameters that depend on the soil properties, initial water content and distribution, and so forth.

In addition to uniform profiles for which it was originally derived, the Green-Ampt equation has been used with good results for profiles that become denser with depth (Childs and Bybordi 1969) and for soils with partially sealed surfaces (Hillel and Gardner 1969). It may also be used for nonuniform initial water contents (Bouwer, 1969) and Morel-Seytoux and Khanji (1974) showed that it retained its original form when the effects of air movement were considered for deep soils.

The model requires input for infiltration in the form of a table of A and B versus initial water table depth. Methods for estimating S_f based on soil texture were presented by Rawls et al. (1983). When rainfall occurs, A and B values are interpolated from the table for the approximate water table depth at the beginning of the rainfall event. The same A and B values are used as long as the rainfall event continues. An exception is when the water table rises to the surface, at which point A is set to A = 0 and B is set equal to the sum of the drainage, ET, and deep seepage rates.

Surface Drainage

Surface drainageis characterized by the average depth of depression storage that must be satisfied before runoff can begin. In most cases it is assumed that depression storage is evenly distributed over the field. Depression storage may be further broken down into a microcomponent representing storage in small depressions due to surface structure and cover, and a macrocomponent which is due to large surface depressions and which may be altered by land forming, grading, and so forth. A field study (Gayle and Skaggs 1978) showed that the microstorage component varies from about 0.1 cm for soil surfaces that have been smoothed by weathering to several centimeters for rough plowed land. Macrostorage values for eastern North Carolina fields varied from nearly 0 for fields that have been land formed and smoothed or that are naturally on grade to >3 cm for fields with numerous pot holes and depressions or which have inadequate surface outlets.

Subsurface Drainage

The method used in DRAINMOD to calculate drainage rates is based on the assumption that lateral water movement occurs mainly in the saturated region. The effective horizontal saturated hydraulic conductivity is used, and the flux is evaluated in terms of the water table elevation midway between drains and the water level or hydraulic head in the drains. Several methods are available for estimating the drain flux including the use of numerical solutions to the Boussinesq equation. However, Hooghoudt's steady state equation, as used by Bouwer and Van Schilfgaarde (1963), was selected for use in the present version of DRAINMOD. This equation may be written as,

$$q = \frac{8 K d_e m + 4 K m^2}{C L^2} \qquad (5)$$

where q is the flux in cm/h, m is the midpoint water table height above the drain (fig. 1), K is the equivalent lateral hydraulic conductivity, d_e is the equivalent depth from the drains to the impermeable layer, and L is the distance between drains, and C is the ratio of the average flux to the flux at a point midway between drains. Solutions based on a water balance at the midpoint and a drainage rate given by equation 5 are compared to numerical solutions of the Boussinesq equation in figure 2. While good agreement was obtained when a constant C = 1.0 was used, almost exact agreement with the Boussinesq solutions was found when C was allowed to vary with the water table elevation, y. The present version of the model uses C = 1.0, however.

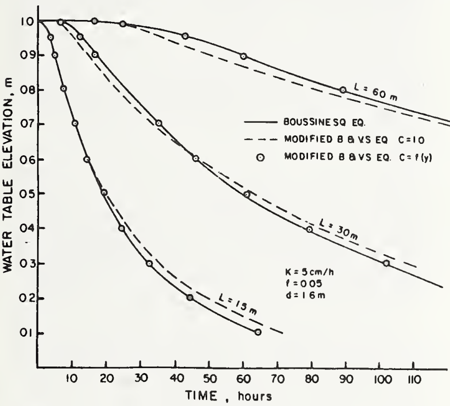

Figure 2. Midpoint water table drawdown as predicted by solutions to the Boussinesq equation and by a simplified model which uses the Bouwer and Van Schilfgaarde 1963) equation.

Hooghoudt (Van Schilfgaarde 1974) characterized flow to cylindrical drains by considering radial flow in the region near the drains and applying the D-F assumptions to the region away from the drains. The Hooghoudt analysis has been widely used to determine an equivalent depth, d_e, which, when substituted for d in figure 1, will tend to correct drainage fluxes predicted by equation 5 for convergence near the drains. Moody (1967) examined Hooghoudt's solutions and presented the following equations from which d_e can be obtained:

For $0 < d/L < 0.3$

$$d_e = \frac{d}{1 + \frac{d}{L}\left\{\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - \alpha\right\}} \qquad (6)$$

in which

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{d}{L}\right)^2 \qquad (7)$$

and for $d/L > 0.3$

$$d_e = \frac{L\pi}{8\left\{\ln\left(\frac{L}{r}\right) - 1.15\right\}} \qquad (8)$$

in which r = draintube radius. Usually α can be approximated as $\alpha = 3.4$ with negligible error for design purposes (Van Schilfgaarde 1974).

For real, rather than completely open draintubes, there is an additional loss of hydraulic head due to convergence as water approaches the finite number of openings in the tube. The effect of various opening sizes and configurations can be approximated by defining an effective draintube radius, r_e, such that a completely open draintube with radius r_e will offer the same resistance to inflow as a real tube with radius r (Mohammad and Skaggs 1983).

The methods discussed above for predicting drainage flux assume a curved (elliptical) water table completely below the soil surface except at the midpoint, where it may be coincident with the surface. However, in some cases, the water table may rise to completely inundate the surface, with ponded water remaining there for relatively long periods of time. Then the D-F assumptions will not hold as the streamlines will be concentrated near the drains with most of the water entering the soil surface in that vicinity. Kirkham (1957) showed that in one case more than 95 percent of the flow entered the surface in a region bounded by $\pm$ one-quarter of the drain spacing. Drainage flux for a ponded surface can be quantified using an equation derived by Kirkham (1957):

$$q = \frac{4k(t + b - r)}{gL} \qquad (9)$$

where t is the depth of water on the surface, b is the depth from the surface to the impermeable layer, r is the draintube radius, and g is a geometric factor expressed as in series form by Kirkham (1957).

Use of equations 5 or 9 assumes that drainage is limited by the rate of soil water movement to the lateral drains and not by the hydraulic capacity of the draintubes or of the outlet. Usually, the sizes of the draintubes are chosen to provide a design flow capacity, which is called the drainage coefficient, D.C. Typically, the D.C. may be 1 to 2 cm per day (about 3/8 to 3/4 inches per day), depending on the location and crops to be grown. When the flux given by equations 5 or 6 exceeds the D.C., q is set equal to the D.C. in DRAINMOD as suggested by Chieng et al. (1978).

Subirrigation

When subirrigation is used, water is raised in the drainage outlet so as to maintain a pressure head above the center of the drain of y_o (refer to the broken curve in fig. 1). Then the equation corresponding to equation 5 for flux is

$$q = \frac{4K}{L^2}(2\, h_o\, m + m^2) \qquad (10)$$

where $h_o = y_o + d_e$ is the equivalent water table elevation at the drain and m is defined as $m = h_m - h_o$, with h_m being the equivalent water table elevation midway between the drains. For subirrigation, $h_o > h_m$ and both m and q are negative. Convergence losses at the drain are treated in the same manner as in drainage by using the equivalent depth to the impermeable layer, d_e, rather than the actual depth, d, to define h_o in equation 10. Equation 10 was derived by making the D-F assumptions and solving the resulting flow equation for steady state evaporation from the field surface at rate q. The magnitude of q increases as m becomes more negative, that is, as h_m becomes smaller, until the water table at the midpoint reaches the equivalent depth of the impermeable layer, $h_m = 0$. For deeper midpoint water table depths, which can occur because the actual depth to the impermeable layer is deeper than the equivalent depth, equation 10 predicts a decrease in the magnitude of q. Ernst (1975) observed that this is inconsistent with the physics of flow since the maximum subirrigation rate should occur when the midpoint water table reaches the impermeable layer. He derived the following equation to correct these deficiencies:

$$q = \frac{4K\, m\, (2h_o + \frac{h_o}{D_o}\, m)}{L^2} \qquad (11)$$

where $D_o = y_o + d$, d is the distance from the drain to the impermeable layer, and h_o is the same as defined previously, $h_o = y_o + d_e$. Equation 11 is used in DRAINMOD to predict subirrigation flux.

Evapotranspiration

The determination of evapotranspiration (ET) is a two-step process in the model. First the daily potential evapotranspiration (PET) is calculated in terms of atmospheric data and is distributed on an hourly basis. The method developed by Thornthwaite (1948) is usually applied to calculate PET, although other methods (Penman 1956, Jensen et al. 1963) may be used if input data are available. PET is distributed at a uniform rate for the 12 hours between 6:00 AM and 6:00 PM. Hourly PET is set equal to zero for any hour in which rainfall occurs. After PET is calculated, checks are made to determine if ET is limited by soil water conditions. If soil water conditions are not limiting, ET is set equal to PET. When PET is higher than the amount of water that can be supplied from the soil system, ET is set equal to the smaller amount.

When the water table is near the surface or when the upper layers of the soil profile have a high water content, ET will be equal to PET. However, for deep water tables and drier conditions, ET may be limited by the rate that water can be taken up by plant roots. Approximate methods are used (Skaggs 1980) to estimate water available for ET due to upward flux from the vicinity of the water table and to storage in the root zone. The relationship between maximum steady upward flux and water table depth is one of the inputs to DRAINMOD.

Rooting Depth

The effective rooting depth is used in the model to define the zone from which water can be removed as necessary to supply ET demands. Since the simulation process is usually continuous for several years, an effective depth is defined for all periods. When the soil is fallow the effective depth is defined as the depth of the thin layer that will dry out at the surface. When a second crop or a cover crop is grown, its respective rooting depth function is also included. The rooting depth function is read in as a table of effective rooting depth versus date.

This method of treating the rooting depth is at best an approximation. The depth and distribution of plant roots are affected by many factors in addition to crop species and date after planting. These factors include physical barriers such as hardpans and plowpans, chemical barriers, fertilizer distribution, and tillage treatments. One of the most important factors influencing root growth and distribution is soil water. This includes both depth and fluctuation of the water table as well as the distribution of soil water during dry periods. Since the purpose of the model is to predict the water table position and soil water content, a model which includes the complex root growth processes is needed to accurately characterize the change of the root zone with time.

FIELD EVALUTION OF THE MODEL

Field experiments were conducted over a 5-year period at three locations in the N.C. Coastal Plains to test the reliability of the model. Three soil types and five different drainage system designs were included in the experiment, from which 21 site years of data were obtained. Rainfall intensity and water table elevations were measured continuously at each site, and the observed day end water table elevations were compared to predicted values. Effective lateral hydraulic conductivity values were measured in the field using both auger hole and water table

drawdown methods. Numerous other field and laboratory measurements were made for each soil to determine input soil property and site parameter data.

Comparison of predicted and measured water table elevations were in good agreement. The average absolute deviation between predicted and observed water table depths for 21 site-years of data (approximately 7,400 pairs of daily predicted and measured values) was 8.1 cm. Results are described in detail by Skaggs (1982).

DRAINMOD has also been tested using 8 years of field data from Ohio (Skaggs et al. 1981). In that study predicted and measured outflow volumes were compared for field plots with surface drainage alone, subsurface drainage alone, and for plots with both surface and subsurface drainage. Further testing was conducted for a tight silt loam soil in Louisiana by Gayle et al. (1983) and for irrigated California soils by Chang et al. (1983). Good agreement between predicted and measured results was found in all three studies.

SUMMARY

This paper gives a brief description of a computer model for simulating the operation of drainage and water table control systems. The model, DRAINMOD, was developed for design and evaluation of multicomponent systems which may include facilities for subsurface drainage, surface drainage, subirrigation or controlled drainage, and irrigation of wastewater onto land. The model is based on a water balance in the soil profile and is composed of a number of components, incorporated as subroutines, to evaluate the various mechanisms of water movement and storage in the profile. In order to simplify the required inputs and make them consistent with available data, approximate methods are used for most components. Several field studies to evaluate the reliability of the model are referenced in the paper.

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MODELING SEEPAGE FROM EARTHEN-FILLED DAMS

J. W. Naney and C. R. Amerman[1]

INTRODUCTION

Seepage, as implied herein, means water temporarily stored as surface water in a reservoir environment and introduced to the ground water flow system by means of flow through a porous medium at some later time. Damaging effects of such seepage may result from, or be worsened by, the construction of an earthen-filled dam across a stream. Therefore, an estimate of seepage effects should be made in any hydrologic model which predicts flow where such structures either exist, or may be built during the predictive period of the model. The purpose of this paper is to identify the impacts of seepage on the hydrologic system being modeled and document some modeling approaches available for quantifying both the onsite and downstream effects of seepage.

BACKGROUND

The number of earthen-filled dams built under the Soil Conservation Service, USDA assistance programs as of June 30, 1969, include 5,282 multipurpose structures; 9,751 floodwater retarding structures; 23,400 diversions; 45,211 irrigation storage structures; and 1,700,353 farm ponds, including "dugouts" (SCS 1970). The type and magnitude of problems associated with seepage are varied and depend on local environmental factors such as geology, soil, hydrology, geochemistry, meteorology, and biology. The types of problems associated with seepage are shown qualitatively in figure 1.

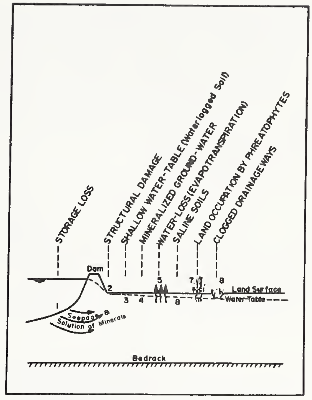

Figure 1. Some seepage problems associated with earthen-filled dams. (From Yost and Naney 1975)

THEORY OF MODEL DEVELOPMENT AND AVAILABLE MODELS

Bachmat et al. (1980) presented an inventory of 193 numerical models used to solve ground water management problems. The models reported are catagorized as follows: flow (138), mass transport (39), heat transport (9), deformation (8), and other (6). Nineteen are identified as stream-aquifer relation models, and nine are flow pattern models.

Amerman and Naney (1982) followed the development of the equation for confined aquifers by Jacob (1950) through the form in which S/T appears:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = \frac{S}{T}\frac{\partial H}{\partial t} \qquad (1)$$

where $S = \theta\gamma_o\ b(\beta + \alpha/\theta)$;

$T = Kb$;

and b = aquifer thickness.

The term S is called the coefficient of storage, and is the volume of water released from storaged by a unit decrease in head in a vertical column of unit cross-sectional area. The term T is called transmissivity or transmissibility.

Prickett and Lonnquist (1971), Trescott et al. (1976), and others added a volumetric flux term to equation 1, removed the assumption of isotropy, and oriented the coordinate axes parallel to the principal components of the transmissivity tensor, giving

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y\frac{\partial H}{\partial y}\right) = S\frac{\partial H}{\partial t} + W \qquad (2)$$

where T_x and T_y are x and y components of transmissivity and W is the volumetric flux of recharge or withdrawal per unit surface area.

Prickett and Lonnquist (1971) and Trescott et al. (1976) developed two-dimensional finite difference models for equation 2; while Gupta et al. (1975) presented a three-dimensional finite element model based on it. Numerous other models have been developed as well, as indicated earlier.

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Four types of numerical solutions, each employing finite-difference techniques for solving the ground water flow equations listed above, were described by Trescott et al. (1976). These are line successive over-relaxation, line successive over-relaxation plus two-dimensional correction, alternating direction implicit procedure, and strongly implicit procedure. The authors also compared numerical results of the four finite difference techniques.

Another solution to the ground-water flow equation 2 is found in the finite difference technique used by Nelson (1962). Nelson used both over-relaxation and under-relaxation techniques, employing the Gauss-Seidel predictor-corrector method for a node-by-node solution of the difference equation, beginning with an initial head estimate.

Winter (1976) modeled two-dimensional porous media flow systems for which one or more lakes were included on the upper boundary. Later, he expanded the study to include three dimensions and solved a variation of the steady state form of equation 2 by finite differences (Winter 1978).

MODEL APPLICATION

Winter (1976) applied modeling techniques to lakes in glacially deposited environment and used vertical strips to generate piezometric heads up, beneath, and down gradient from such lakes. He found the existence and position of the stagnation point that is, the point of minimum head on the divide separating a zone of local flow from larger magnitude flows, to be a major factor controlling both the occurrence and rate of seepage from these lakes. A barrier to water seeping from the lake into the ground-water system is established when a stagnation point is present with head greater than the lake. An example of how the presence of a stagnation point beneath one lake in a two lake system affects lake seepage is shown in figure 2.

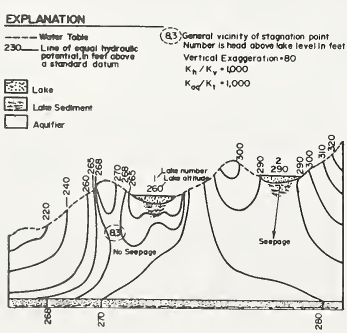

Figure 2. Diagram showing the effect of a stagnation point on lake seepage in the presence of a highly permeable aquifer at depth. (Modified from Winter 1976.)

Naney (1974) adapted a model developed by Nelson (1962) to predict seepage flow and direction of flow from a Soil Conservation Service floodwater-retarding structure on a sandy alluvium in the southern plains of the United States. He found an important feature of seepage to be its impact on the direction of flow near the lake and downstream from the dam for several hundred feet (Naney et al. 1976). The changes in flow direction which may result in longer flow paths in many geologic environments may increase both residence time in the subsurface and the opportunity for an increase in either chemical or nutrient content.

The method used to study ground-water travel time requires a flow net of hydraulic potential contour lines and stream lines, as shown conceptually for a small watershed without and with a lake in figure 3. Seepage velocities can be computed directly from the flow net using Darcy's equation to describe the seepage velocity within a element of the flow net.

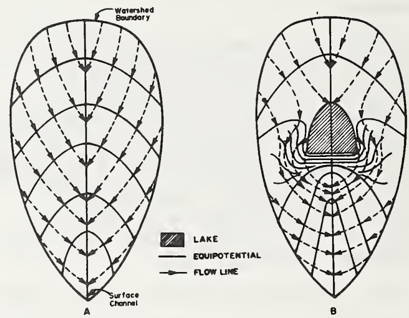

Figure 3. Groundwater flow network without (A) and with (B) dam.

SUMMARY

The effects of seepage from an earthen-filled dam vary with geologic, climatologic, and hydrologic conditions of the dam site. In the case of small agricultural watersheds these effects may significantly alter the quality and quantity of downstream water flow. For this reason, a mathematical model developed for predicting water, sediment or chemical-nutrient discharge from such watersheds should also be capable of predicting the impacts of seepage within the modeled system.

The changes in ground-water flow which occur as a result of seepage may influence both the residence time and the horizontal and vertical movement of water in the subsurface. Therefore, to the extent possible, data for any watershed to be studied should include the hydraulic characteristics of the subsurface flow regime and a defintion of boundary conditions near any earthen-filled dam site.

The authors have presented theoretical and physical factors to be considered when modeling seepage flow. Additionally, some examples are presented of efforts to improve the understanding of such flows, through the use of modeling techniques.

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SIMULATION OF DRAINTILE FLOW IN CREAMS2

R. E. Smith[1]

Figure 1 illustrates the simulation of the action of draintiles in CREAMS2. The superelevation of water table above the parallel drain is assumed to describe a half-elliptic shape, with a storage volume V, between drains equal to:

$$V = \phi \int_{o}^{y_s} h_m dy \simeq \phi \bar{h} y_s$$

where ϕ = porosity, and other variables are defined graphically in figure 1. The flux through the draintiles is a quadratic function of the maximum height, h_m (Bouwer and Van Schilfegaarde, 1963). The unsaturated flux from above, f(z,t), can be assumed to be stepwise constant and is found from the unsaturated flow solution. With $\bar{h}$ a function of h_m, the general linear equation

$$\phi y_s \frac{d\bar{h}}{dt} = y_s f - q_d(\bar{h}) \qquad (1)$$

can be solved for the general relation

$$h = \frac{1}{2a} \left\{ \frac{(b+g)P\exp F-(b-g)}{1 - P\exp F} \right\} \qquad (2)$$

in which $g = \sqrt{b^2 + 4af}$

a and b = parameters in Houghoudt's equation,

$$q_d = ah_m^2 + bh_m$$

$$P = (2ah_o + b + g)/(2ah_o + b - g)$$

$$\exp F = \exp(-Kg\Delta t)$$

K = saturated conductivity in draintile soil layer

Δt = time interval over which f is assumed constant for solution

and $h_o = h_m$ at $t = 0$.

This method follows with equal accuracy the rising and falling of the water table above or below a drain, and works in tandem with the unsaturated flow above the water table.

DRAINTILE SIMULATION

Dynamic balance of saturated zone:

$$V = \phi \int_{o}^{y_s} h_m dy \approx \phi \bar{h}\, y_s$$

unsaturated flux = f(z,t)

$$\frac{dV}{dt} = \phi y_s \frac{d\bar{h}}{dt} = y_s f(z,t) - q_d(h_m)$$

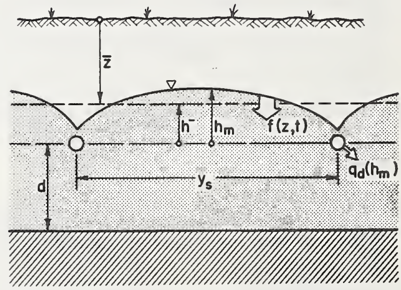

Figure 1.--Definition diagram for the draintile computations in CREAMS2.

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DAILY WEATHER FORECAST RAINFALL PROBABILITY AS AN INPUT TO A WATER MANAGEMENT SIMULATION MODEL

James L. Fouss[1]

INTRODUCTION

The design of dual purpose systems for subsurface drainage and subirrigation is of major interest today in much of the humid and semihumid areas of the United States. The computer simulation model DRAINMOD can be used to predict the performance of such water management systems over a long period of climatological record (Skaggs 1980, 1982). Recorded weather data and site specific soil and system design parameters are required as inputs to the model to simulate system operation. The computer program determines several operational parameters during the simulation, which aid in evaluating various designs and modes of operation. The Soil Conservation Service, USDA, is currently using DRAINMOD to design drainage and water management systems in several humid-region States (SCS-USDA 1983).

A common method of operation for drainage-irrigation systems is to maintain a constant water level (elevation) at the outlet/inlet (O/I) of the subsurface conduits. Another method is to lower the water level as the plant root system develops. DRAINMOD can accomodate these control concepts in the system simulation process. Such modes of control are limited, however, because the O/I water level is relatively fixed, even during periods of extreme excess or deficit water. Other types of control have been investigated for dual purpose systems. Warner (1972) used rainfall prediction as an input for a management-decision model that was coupled with a simplified controlled-drainage/ subirrigation-simulation model. A daily decision was made to raise, lower, or leave unchanged the O/I water level based upon the probability of rainfall over the next 24 hours. Smith et al (1982) established operating criteria for regulating the O/I water level in response to minimum and maximum water table depths midway between drain lines; Smith (1983) developed a sophisticated simulation model for this control method. Fouss (1983) developed a subroutine for DRAINMOD to simulate automatic feedback control of the O/I water level, based on the deviation of the midpoint water table from a desired depth.

This paper presents a method for using rainfall probability information from records of daily weather forecasts as inputs to DRAINMOD to "override" the system control when a high probability of rainfall occurs. The purpose of the "override" is to more rapidly draw down the water table to the drain level, thus reducing the duration of excess soil water in the root zone if rainfall occurs. Weather forecast data must represent the same geographic area as the climatological data. A daily management decision is made for the simulated water control system, based upon the probability of rain today, tonight, and/or tomorrow. This process is illustrated by a simulated "override" of the constant O/I mode of control for a specified probability of rainfall. That is, the O/I water level is lowered to drain depth during each override event.

RAINFALL PROBABILITY DATA

The National Weather Service issues weather forecasts four times a day in most areas of the country. The early morning forecast was selected as the most likely to get the attention of a farmer. The forecast includes the probability of rainfall for three 12-hours time periods: "today," "tonight," and "tomorrow." Forecasts issued later in the day are normally updates of the morning forecast. Some forecasters also give predictions on the amount of rainfall expected, but this is done locally and the criteria are not standarized. The criteria and procedures for determining the probability of rainfall issued in the weather forecasts are standardized throughout the United States by the National Weather Service (Muller 1983). Each weather service station maintains records of all forecasts issued for the past 5 years. The current forecasting standard has been in effect for approximately 6 years.

For the study reported here, local weather forecasts for the years 1979 through 1982 were obtained from the National Weather Service station at Baton Rouge, LA. Probabilities were stated in even multiples of 10 percent, from 20 to 90, with the only exceptions being"less than 20 percent" and "near 100 percent." A probability stated as less than 20 percent or not stated, was coded as zero. If the probability was stated as "near 100 percent," it was coded as 100.

In southern Louisiana, rainfall events during the summer months occur most frequently in the afternoon and early evening and normally result from convective storms. Thus, both the events and the forecasts may be assumed to be essentially independent. Accordingly, the equation for computing (each morning) the probability of realizing at least one rainfall event "today," "tonight," or "tomorrow" is (after Warner 1972, Korn and Korn 1968.)

$$P[E1 \cup E2 \cup E3] = 1 - \{1-P[E1]\}*\{1-P[E2]\}*\{1-P[E3]\} \quad (1)$$

where: P[E1], P[E2], and P[E3] are the probabilities of rainfall for "today," "tonight," and "tomorrow," respectively; and E1, E2, and E3 are statistically independent events.

Warner (1972) related that if rainfall occurred due to a frontal storm pattern, then the events and the forecasts may be dependent, because a

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portion of the same weather data is analyzed in determining the forecasts. The frontal storm patterns were assumed to be independent, however, which probably provided some positive bias in the estimation of the combined daily probability.

Hourly rainfall records for years 1979-1982 were obtained for the Louisiana State University Ben Hur Research Farm, Baton Rouge; the local forecast applies to this area. Annual and growing season rainfall totals for the period of study are given in table 1, along with 16-year averages. A regression analysis of the recorded rainfall amounts vs. forecast probabilities of rain was conducted in a manner similar to that reported by Warner (1972). This analysis provided polynominal equations expressing expected rainfall amount as a function of probability of rainfall in the daily weather forecast for 12-, 24-, and 36-hour periods. The details of the regression analysis procedure are not presented here; only the results as applied to the simulation process.

Table 1.--Annual and growing season rainfall totals, Ben Hur Research Farm, Louisiana State University, Baton Rouge, LA

Year	Annual rainfall (cm)	Growing season rainfall[1] (cm)
1979	167.2	96.1
1980	166.0	102.1
1981	117.2	65.5
1982	138.0	57.2
16-year average	137.3	71.7

[1]Approximate growing season from April 1 to August 30.

Because of the extreme variability of the rainfall amount for a given probability of rainfall in the Baton Rouge area, the regression coefficients for the previously noted statistical analyses were very low; thus, predicting amount of rainfall to be expected based upon the weather forecast was poor. The local forecasts were quite good, however, in predicting the occurrence of rainfall within a 36-hour period, but for any 12-hour period the reliability was not as good. For the combined 36-hour period forecast, the reliability of predicting an amount of rainfall equal to or greater than a given total improved with increasing probability of rainfall. Table 2 presents a summary of the recorded total rain for a 36-hour period vs. the combined 36-hour rainfall probability for the Baton Rouge area during the 1979-82 period of record used in this study. For each given rainfall threshold amount, the combined rainfall probability (as computed by equation 1) is shown, for which the total 36-hour rainfall total equaled or exceeded the given amount for 30, 50, and 70 percent of rainfall events recorded.

Table 2.--Combined rainfall probability (for "today," "tonight," and "tomorrow") at which 30, 50, and 70 percent of occurrences of rain had amounts of rainfall equal to or greater than various threshold amounts, Baton Rouge, LA

Threshold rainfall amount (in 36-hour period) (inch)	(cm)	Combined rainfall probability (Equation 1) at which: 30% rainfall equalled or exceeded threshold	50%	70%
0.01	0.025	[1]32	52	80
		[2]35	56	79
0.12	0.300	48	76	88
		49	75	88
0.25	0.630	63	82	--
		61	82	96
0.38	0.960	71	87	--
		72	83	96
0.50	1.270	76	93	--
		76	89	97
0.75	1.900	85	--	--
		84	94	98
1.00	2.540	95	--	--
		93	98	100
1.25	3.170	99	--	--
		97	99	--
1.50	3.810	--	--	--
		99	100	--

[1]Upper figures are for entire year (1979-82).
[2]Lower figures are for period 91 to 273 days of the year.

SIMULATION PROCEDURE

Based upon the above analysis (re. table 2), the combined probability (for "today," "tonight," and "tomorrow") was selected for computation and use within the simulation model to arrive at daily management decisions concerning the O/I water level adjustment needed, if any. The effectiveness of the weather forecast input as a control override was evaluated by comparing simulation results for the following override features of a constant O/I water level method of control:

(1) No override -- O/I water level constant at 55 cm depth during growing season;

(2) Shallow water table override when WT depth is less than 50 cm (55.0 - 5.0);

(3) Override when the rainfall "record" for "tomorrow" $\geq$ 1.50 cm, and when the WT is above the drain; and

(4) Override when the combined probability of rainfall for "today," "tonight," or "tomorrow" $\geq$ 85 percent, and WT is above the drain.

The simulation in 3 above is accomplished in the computer program subroutine by searching the

rainfall data record for "tomorrow" prior to simulating the system operation for "today." The O/I water level is lowered to drain depth at 6:00 a.m. for each override event. The water level is raised again at 6:00 a.m. on the following day, provided the WT depth at the midpoint is within a specified tolerance of the set point depth (here, 55 $\pm$ 5 cm); otherwise, the water level is left at drain depth for another day.

A Commerce silt loam soil typical in southern Louisiana was selected, and a uniform lateral hydraulic conductivity of 1 cm/h for the effective soil profile depth was assumed. Other soil parameters and field operational parameters, reported in detail by Fouss (1983) for DRAINMOD simulations conducted for this soil were used. The parameters included an average drainable porosity of 6.0 percent and a steady-state upward flux of 0.026 cm/h for a water table depth of 60 cm. The following system design parameters were used: drain depth = 100 cm, drain spacing = 15.2 m, and drain diameter = 10 cm (inside diameter).

The performance parameter of interest was excess soil water within 30 cm of the ground surface (the root zone), expressed as SEW30. Further, relative yields were obtained using the corn yield prediction subroutine in DRAINMOD (Skaggs et al 1982). The controlled, constant water level for the O/I was not optimized for maximum relative yield because of the short record of climatological data. Previous long-term simulation studies (Fouss 1983), using 20-year climatological records from New Orleans, indicated that an average midpoint water table depth of 80-90 cm maximized relative corn yield for the Commerce silt loam soil. This was accomplished with a constant O/I water level of 55 to 65 cm below the ground surface for the subsurface conduit system design considered here. A constant O/I water level of 55 cm was selected for the simulations reported here, to insure that the water table at the midpoint between drains would not fall more than 10 cm below the drain for longer than 10 days during the growing season, for the years of rainfall and weather forecast record (1979-82). Yields are used to make general comparisons between system management methods and to illustrate trends or concepts.

SIMULATION RESULTS AND DISCUSSION

The simulation results for the subdrainage-subirrigation system are illustrated graphically in figure 1, where the outlet/inlet water level is controlled at a constant elevation during the growing season; in figure 2, where the "known" rainfall record (data) for "tomorrow" permits a simulated override of the constant water level control "today;" and in figure 3, where the daily weather forecast is used to decide when to override the constant water level control. The simulated fluctuation of the water table depth at the midpoint between drain lines, and the controlled depth of the outlet/inlet water level are shown for each day of the example year 1979,

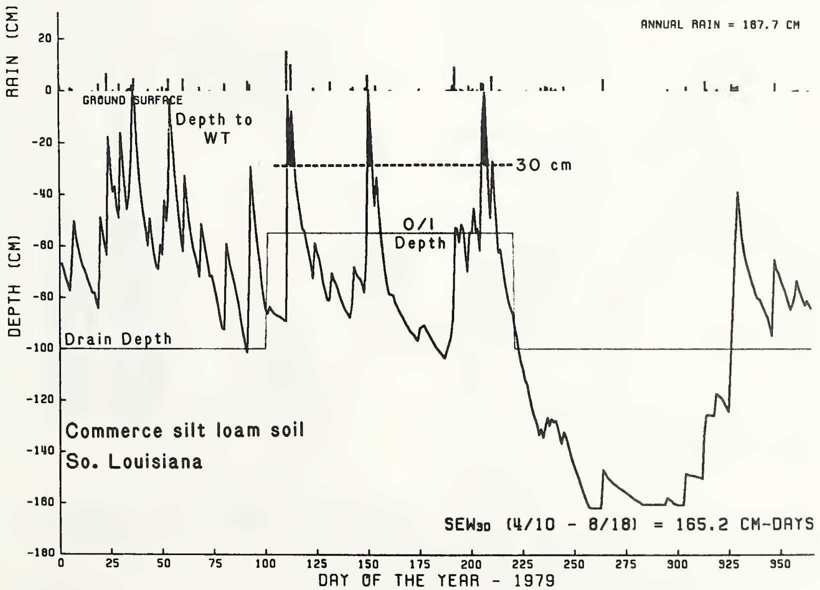

Figure 1.--Simulated midpoint water table fluctuations using constant outlet/inlet water level control during the growing season.

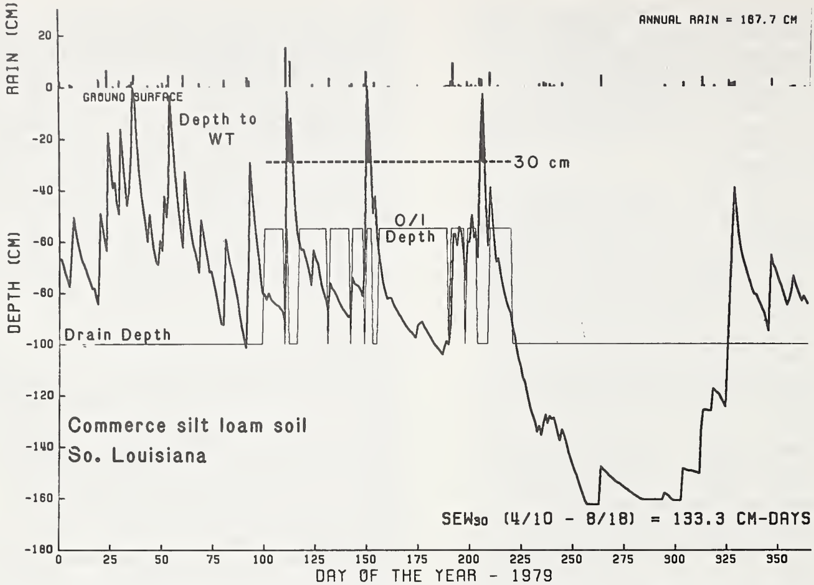

Figure 2.--Simulated midpoint water table fluctuations using "override" of constant outlet/inlet water level when "known" rain "tomorrow" (from climatological record) is ≥ 1.5 cm.

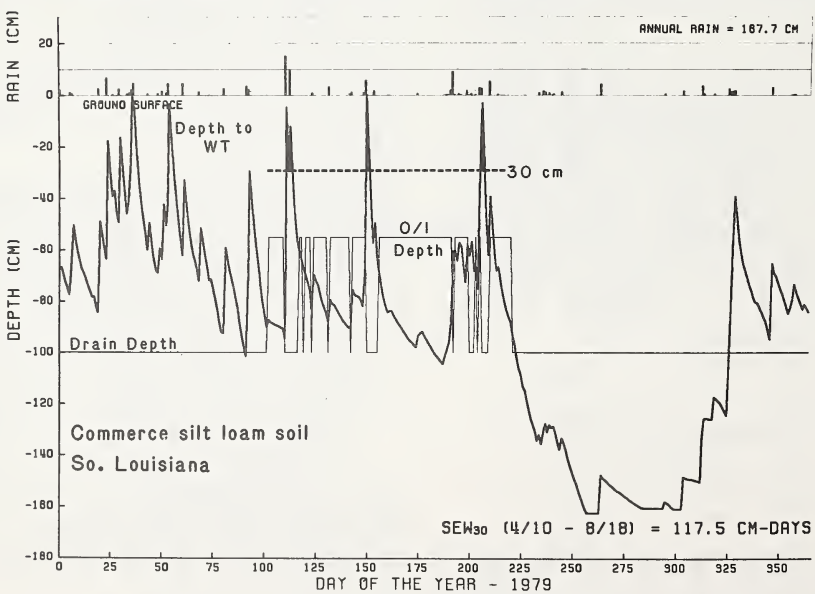

Figure 3.--Simulated midpoint water table fluctuations using "override" of constant outlet/inlet water level when rainfall probability ≥ 85% "today," "tonight," or "tomorrow."

Table 3.--Summary of simulation results for constant outlet/inlet water level control with and without control "override" options

	Description of system[1] control method	Year	SEW30 at midpoint (cm-da)	Average[2] midpoint WT depth (cm)	Average[2] O/I depth (cm)	Days O/I at drain	Relative corn yield (%)
A)	No override-constant O/I water level (55 cm)	1979	165.2	70.2	55.0	0	81.1
		1980	199.6	74.5	55.0	0	62.1
		1981	1.0	80.3	55.0	0	100.0
		1982	69.6	83.1	55.0	0	88.1
B)	Shallow WT override if WTD < 50 cm	1979	135.0	74.2	62.6	18	84.6
		1980	130.0	78.3	63.0	19	75.5
		1981	0.0	82.8	59.2	9	100.0
		1982	52.0	84.9	58.1	6	91.9
C)	Rain tomorrow override if rain ≥ 1.5 cm	1979	133.3	73.7	63.0	20	84.2
		1980	141.7	78.6	63.7	21	73.1
		1981	0.0	83.2	60.0	12	100.0
		1982	67.5	84.4	58.1	7	88.5
D)	Probability of rain override if P ≥ 85%	1979	117.5	75.7	66.0	26	86.2
		1980	126.4	79.0	64.5	23	76.2
		1981	0.0	85.0	61.5	15	100.0
		1982	48.2	87.2	62.2	17	92.7

[1]Drain depth = 100 cm; drain spacing = 15.2 m; lateral K = 1 cm/h
[2]Actual growing season from April 1 to August 8; controlled period.

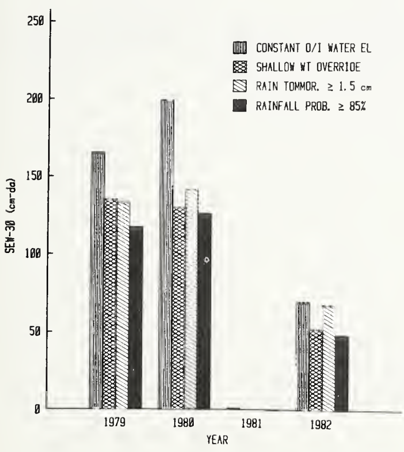

Figure 4.--Seasonal excess soil water in the root zone (SEW30) vs. year for four types of system control.

a relatively wet season (see table 1). Key performance parameters for the four different methods of "override" of the O/I water level control are summarized in table 3 for the 1979-82 period. Figure 4 presents a bar-graph comparison of the SEW30 performance indicator for the four systems over the 4-year period.

The override based on a combined probability of rainfall ≥ 85 percent (fig. 3) was selected as the threshold value from simulation runs for 80, 85, and 90 percent probability, which reduced SEW30 by an average 33, 33, and 27 percent, respectively, compared to constant O/I water level control. Override because of a shallow water table event (less than 50 cm deep) provided about the same reduction in SEW30 as the 85 percent probability forecast. The special simulation technique involving "known" rain "tomorrow" ≥ 1.5 cm (that is, by computer searching the actual rainfall "record" for tomorrow before simulating today) to trigger an override event, provided a similar control of the midpoint water table depth (fig. 2) and reduction in SEW30 (table 3), as when the 85 percent probability forecast was used. This rainfall threshold amount was selected from simulations for 1.0, 1.5, and 2.0 cm rainfall for "tomorrow." The number of days during the growing season that each type of override caused the O/I water level to be maintained at drain depth appears to be a good comparative indicator of performance (see table 3). The override feature significantly increased the predicted relative corn yield over that with constant O/I water level control only in 1980 (table 3). Rainfall during the 1980 growing season was significantly above normal (table 1).

An important result and observation from this study is that the rainfall probability data included in daily weather forecasts by the National Weather Service may provide useful and reliable information to aid in making daily management decisions for operation of subsurface water control facilities. Additional study, by simulations and field trials, needs to be conducted; longer periods of weather forecast records are needed to expand the study. It is recommended that modelers and researchers consider using weather forecast information as inputs to other simulation models, particularly those that involve making farm management decisions concerning operations (in the real world) that would be delayed, altered, or otherwise affected by rainfall (for example, applying fertilizer, chemical sprays, tillage operations, planting, and harvesting). Models such as EPIC, ALMANAC, and CREAMS2, which have been developed through cooperative USDA-ARS research, could perhaps be modified to incorporate rainfall probability inputs to their respective simulation processes.

SUMMARY

A method was developed for using rainfall probability information from records of daily weather forecasts as an input to the water management simulation model DRAINMOD. The new input was used to make daily decisions concerning manual or semiautomatic "override" of the regulated water level at the outlet/inlet for a simulated subsurface-drainage/subirrigation system. If the combined probability of rainfall for "today," "tonight," or "tomorrow" was greater than or equal to 85 percent, the outlet/inlet water level was lowered to drain depth "today." This control override feature reduced the predicted duration of excess soil water in the root-zone, compared to that where the outlet/inlet water level was maintained at a constant elevation, especially during growing seasons with excess rainfall.

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MANAGEMENT OF WATER IN AGRICULTURAL DRAINAGE DISTRICTS

J. E. Parsons, C. W. Doty, and R. W. Skaggs[1]

INTRODUCTION

Many areas in the Southeastern Coastal Plains of the United States require drainage for sustained crop and timber productivity. The lack of suitable drainage outlets in these areas limits the applicability of many water management systems on a fieldwide and areawide scale. A number of these areas have been drained by channelization; the natural channels are dug deeper, widened, and straightened.

During the crop growing season, deep channels draw the water tables down in excess of 1 to 2 m from the soil surface. This, complicated by the fact that the soils are sandy with low water holding capacity in the root zone, greatly limits the water available to the crop. Farmers in these areas have installed irrigation systems to help counteract this. Primary water sources for such irrigation systems are wells and water stored in the drainage channels. But as the crop growing season progresses, drainage channels do not always provide a sufficient water source for the irrigation systems.

An example is the Conetoe drainage district in eastern North Carolina, where 26,000 hectares of land are drained by a network of channels which in some sections are 2.5 m deep. The channel system provides adequate drainage for the area and prevents the once frequent flooding. These deep channels have increased the drought stresses on the crops because the upward movement of water to the root zone in these sandy soils is small for the deeper water tables. Furthermore, with the increased number of irrigation systems in the area, the water available in the channels is often insufficient as the growing season progresses.

A cooperative project between Federal, State, and local groups was initiated in 1979 to study the effects of channel water level control on water management. The federal cooperators are the Agricultural Research Service and the Soil Conservation Service of the U. S. Department of Agriculture. The biological and agricultural engineering department and the soil science department of North Carolina State University are representing the State as cooperators. The local cooperators include the Edgecombe County Drainage District #2, and the local farmers and land owners of the area.

Chosen for detailed study was a 2-mile section of Mitchell Creek, one of the main drainage channels, which has a drainage area of approximately 800 hectares. The land area is flat to gently rolling, with the largest elevation difference being approximately 1.5 m. A dam was installed on Mitchell Creek in 1982. The water level in Mitchell Creek is controlled automatically by the dam. The dam has enabled accurate control of the channel water levels along with providing the required drainage during periods of excess rainfall (Doty et al. 1982).

The overall project objectives are to study the present methods for the design and operation of water management systems and to develop better criteria for such systems. One of the specific project objectives is to develop and test a comprehensive water management model for the analysis and evaluation of agricultural drainage district designs.

A number of models have been developed for describing water flows and storage on a watershed scale and a regional scale. Two such models are those of Freeze (1971) and de Laat et al. (1981).

Freeze (1971) used solutions to the three-dimensional Richard's equation to simulate water movement in a watershed. The difficulty in obtaining the input parameters and the time and expense of the computer simulations make this approach unfeasible in large areas where a number of years of simulation are required. On a regional scale, de Laat et al. (1981) developed a model for the evaluation of water management policies. Their model separates the system into interacting components to simulate the effects of water management policies on regions on the order of 1000 square kilometers. The use of this model on an agricultural drainage district would be difficult without making major modifications. Therefore, we decided to develop a comprehensive model utilizing the appropriate assumptions from the existing models. The purpose of this report is to give an overview of the present model.

THE WATER MANAGEMENT MODEL

The main objective of the model is the simulation of water table changes in response to channel water levels and the weather, specifically, breakpoint rainfall over periods greater than 10 minutes and daily potential evapotranspiration. The channel networks in these areas consist of both parallel and intersecting channels. A typical geometry is given in figure 1. The various channel networks make a two-dimensional saturated flow model necessary to accurately describe water movement near intersecting channels.

Other specific objectives of the model include estimates of water availability in the crop root zone in response to water table changes. Also, for an accurate accounting of water flows within the system, the model should have components to estimate infiltration and surface water storage and flow. The model should be modular so that subsystems, in the form of subroutines, can be easily exchanged with new ones reflecting different assumptions. The computer time should be such that simulations of a year are not cost prohibitive.

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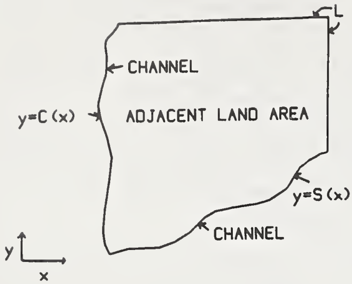

Figure 1. A typical channel geometry.

The overall structure of the model consists of components for water movement in the saturated zone, in the root zone, and on the soil surface. Model input is the first major portion of the model executed. Routines dealing with the root zone water flows consist of calculating the water available in the root zone, finding the amount of upward water movement from the water table, and estimating the amount of infiltration and runoff from rainfall events. The routing of runoff over the area is done by the overland flow component. The saturated soil component simulates the water table changes in response to channel water level changes in main and lateral drainage channels, to field scale water management systems such as surface irrigation and subsurface irrigation and drainage systems, and to the vertical water movement due to addition of rainfall and extraction of water to meet evapotranspiration demands.

A flow chart showing the execution flow of the model is given in figure 2. Short descriptions of the major model components and the assumptions made for their development are given in the following paragraphs.

The saturated soil water movement component consists of the solution of the two-dimensional Boussinesq equation using the finite element method (FEM). This entails assuming that water flows parallel to a horizontal impermeable layer at a given depth. The formulation of the Boussinesq equation is

$$f \frac{\partial}{\partial t} = \frac{\partial}{\partial x} \left(K h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y} \left(K h \frac{\partial h}{\partial y}\right) + R \qquad (1)$$

where f = drainable porosity,
h = height of the water table above the impermeable layer in m,
t = time in days,
K = lateral saturated hydraulic conductivity in m/day,
x, y = cartesian coordinates in m, and
R = rate water enters or leaves the water table vertically in m/day.

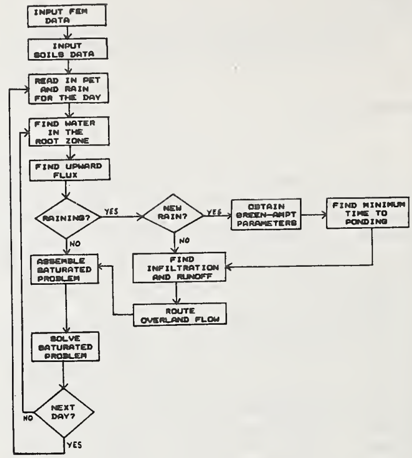

Figure 2. A flow chart of the model.

The drainable porosity, f, and the lateral saturated hydraulic conductivity, K, depend on the soil type and on water table height, h. The rate water enters or leaves the water table vertically, R, is negative for movement of water into the root zone and positive for deep drainage from infiltration water. This rate is assumed to be at the unsaturated soil-saturated soil interface. The boundary conditions are the channel water levels in the drainage channels throughout the area. The finite element solution procedure has been described in detail by Parsons et al. (1982).

In the root zone, the horizontal water movement is assumed to be negligible. At each node throughout the area, the water is balanced in the root zone in response to evaporative demands and rainfall inputs. The mass balance of water in the root zone is done similarly to the methods of Skaggs (1978). The main difference is that the model balances the water by layers, thereby enabling the use of soil horizon data.

To satisfy potential evapotranspiration demands, the upward water movement from the water table into the root zone is computed. This amount replenishes water removed from the root zone to meet the evapotranspiration demands. Any additional water required is withdrawn from the root zone. In cases where the amount in the root zone is not sufficient, the actual evapotranspiration will be less than the potential. The amount which supplied from the water table is used as the recharge term, R, in the solution of equation 1 at the next time step. This provides a coupling between the unsaturated zone and the saturated zone components.

During periods of rainfall, the infiltration rate at each node is estimated using the Green-Ampt equations in the same manner as Skaggs (1978). The portion of the rainfall that infiltrates consists of two parts. The first part is the amount required to bring the soil water in the root zone to a maximum as determined from the soil water characteristic. The remaining infiltrated water is assumed to be available at the unsaturated soil-saturated soil interface as vertical recharge to the water table. This is converted to a rate and provides the term, R, in the solution of equation 1.

The excess water, amount of rainfall not infiltrated, is made available for surface storage and runoff. Surface depression storage is filled, and the remaining excess water goes into surface retention storage on the area represented by the node. The surface retention storage is the portion of water on the soil surface which is available to move in response to surface slope and roughness. This retention storage is available for runoff.

Surface water available for runoff is routed to surrounding nodes, based on the slope of the water on the surface and the land areas associated with each node. The slopes are computed between the nodes using the elevation of the soil surface plus the depth of water in the surface depressions and in the surface retention storage. Although this surface retention component is called a storage, the amount of water in this component will be routed to surrounding nodes at the end of the current time step. The surface water is balanced on a volume basis. Head losses due to surface flow are assumed to be negligible. There are provisions for including surface roughness and frictional head losses. Water arriving at the channel boundaries is assumed to be lost to the channel with no change in channel water level, thereby exiting the system.

The model is mechanistic in nature and the inputs are extensive. Inputs for the saturated component consist of a finite element grid of the study area and the channel boundary nodes where the channel water level will be specified. At each node in the area, the model requires the surface elevation, the maximum depth of surface depression storage, and the initial water table height. The soil type at each node in the area is also specified. This is done by overlaying a soils map onto the finite element grid of the area. The input information for each soil type consists of lateral saturated hydraulic conductivity profiles, K, the relationship of drainable porosity, f, with water table depth, soil water characteristics by soil layer in the deepest root zone expected, amount of vertical water movement from the water table versus water table depth, and the relationship of the Green-Ampt parameters with water table depth.

For each simulation, the output from the model consists of water table depth, soil water in the root zone, vertical recharge to the water table, upward movement of water from the water table to the root zone, infiltration into the root zone, surface depression storage, and surface retention storage at each node. For the channel boundaries, the lateral seepage into the channels and the runoff water into the channels are available.

Presently, the model testing is being done using the Conetoe Creek project data. Details of the current field project are presented elsewhere (Doty et al. 1982 and Doty et al. 1983). For these tests, the time steps are 4 hours for days without rainfall events. On days with rainfall events, a time step of 1 hour is used for periods with rain and 2 hours for periods with no rainfall. Tests are being made to determine the model sensitivity to these time steps.

APPLICATION AND FUTURE MODIFICATIONS

A comprehensive water management model for the evaluation of the design and management of water resource projects has been developed. In particular, the analysis of water management d management of water resource projects has been developed. In particular, the analysis of water management systems for agricultural drainage districts with parallel and intersecting channels can be made. Model development has focused on relatively flat land with naturally high water tables. These areas can be characterized by a network of channels used for drainage.

The model consists of components for the integration of water movement in the saturated soil zone, the root zone, and on the soil surface. These components are coupled in time. Since each of the model's components require different time steps, the choice of time steps for the coupled model takes these into account.

The modular design of the model enables easy testing of the different assumptions and submodels for the respective components. For example, the use of the Richard's equation in place of the present one-dimensional water balance in the unsaturated soil zone has been considered and not been done because of the computational requirements and the cost. Additionally, investigations are being made into coupling an existing channel flow model as a submodel to the hydrologic system we have outlined.

At this time, we are testing and evaluating the model applicability and effectiveness in simulating water table response to the weather patterns and varying channel water levels. After this has been accomplished, the model will be used to evaluate various submodels incorporating different levels of assumptions from more sophisticated to less sophisticated. The end result is to obtain a cost effective model for evaluating water resource project designs based on a number of years of climatic record.

Contribution from the Coastal Plains Soil and Water Conservation Research Center, U. S. Department of Agriculture, Agricultural Research Service, Florence, SC, in cooperation with the North Carolina Agricultural Research Service, North Carolina State University, Raleigh, NC.

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SPATIALLY VARIABLE GROUND-WATER RESPONSE FOR A SMALL WATERSHED

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INTRODUCTION

This paper provides an overview of the ground-water submodel developed for inclusion in SWAM, the Small Watershed Model (DeCoursey 1982). Numerous models have been developed which solve the Laplace equation for saturated ground-water flow, with finite difference or finite element methods being the most widely used solution techniques (Amerman and Naney 1982, Freeze 1971). However, computational time required by these techniques is prohibitive for systems with the number of elements necessary to describe the ground-water response of a mixed-land-use watershed. Herein, we describe a technique which has minimal computational requirements yet simulates both ground-water flow and dissolved chemical concentration input to the channel system of a small mixed-land-use watershed. It is based on simple mass balance and on concepts presented in Liong and DeCoursey (1982) and Liong et al. (1982).

SUBMODEL CONCEPT OF GROUND-WATER FLOW

The subsurface saturated flow region of a catchment is visualized, as in figure 1, to consist of numerous noninteracting flow paths (sections), both parallel and convergent, which contribute ground water to the channel. Spatially varying channel inflow is determined by simulating the separate response of each of these representative sections. Section overlapping is necessary to represent the total watershed area using the idealized flow paths.

Figure 2 is a schematic of the cross section of one such flow pathway. This particular flow path has three recharge input segments, each providing a separate flux rate, i_i, at concentration C_i to the ground water. The saturated portion of the section has effective porosity (storativity), n, and hydraulic conductivity, K_s. The stream is at an elevation h_s above a horizontal impermeable layer, while the water table elevation at the divide is at h_1 above the impermeable lower boundary, or h_d above the stream elevation. The angle of convergence for nonparallel sections is θ, expressed in radians. Such section specifications imply a homogeneous, isotropic, water table aquifer.

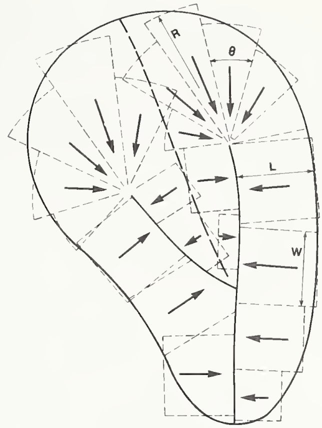

Figure 1.--Schematic of ground-water flow paths.

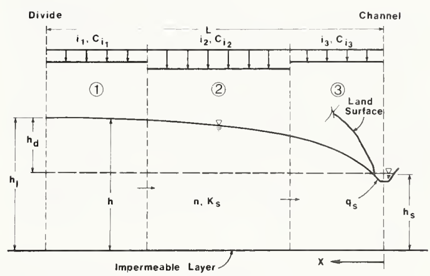

Figure 2.--Schematic of flow path cross section.

THE OPERATIONAL MODEL

The flow portion of the submodel is simple in concept. Each time interval (daily at present) consists of a two-step, recharge-drainage, mass balance computation. Section outflow, q_s, is determined by the change in storage volume within the section during the drainage phase of simulation. We assume the ground-water surface always to be in the steady-state configuration derived using the Dupuit-Forchheimer approximations. The steady-state water table for a parallel flow section, in terms of the water table elevations at the end points of the profile, is

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$$h^2 = h_s^2 + \frac{2x}{L}(h_1^2 - h_s^2) - \frac{x^2}{L^2}(h_1^2 - h_s^2) \quad (1)$$

Similarly, the equation for a converging flow section is

$$h^2 = A \ln r + Br^2 + C \quad (2)$$

where r is radial distance, and

$$A = \frac{(h_1^2 - h_s^2)}{\ln(\frac{R}{r_o}) + \frac{r_o^2}{2R^2} - \frac{1}{2}}$$

$$B = \frac{(h_1^2 - h_s^2)}{2R^2 \ln(\frac{R}{r_o}) - (R^2 - r_o^2)}$$

$$C = h_s^2 - A \ln r_o - B r_o^2$$

where r_o is radial distance from the apex of the section to the stream and R is distance to the divide. Equations 1 and 2 are apropos only to relatively long, shallow flow sections having gentle topographic relief.

To evaluate storage within a section, the area under these curves must be calculated. In the case of the parallel section (equation 1), the integration is done analytically. For the converging flow case, integration of equation 2 cannot be done analytically, but the area under the curve is easily determined using a numerical integration technique; in the model we use Gaussian Quadrature.

In each flow case, i, K_s, and h_1 are not independent. If the values of any two of these variables are specified, the value of the third is fixed. This property of the system is used at the beginning of a simulation to help set initial conditions. In the current version of the model, h_1 and an initial recharge value, i, are specified; the watershed saturated conductivity, K_s, is calculated within the model. The initial recharge value is set equal to the assumed steady-state discharge at the date simulation is to begin. The model could easily be adapted to accept any two of the values and calculate the third therefrom.

Recharge Phase

At the beginning of a time interval, the initial water surface configuration and volume of storage is known, and the individual recharge rate from each input segment in the flow path is passed to the ground water submodel from a ground water-recharge submodel in SWAM. These recharge rates are summed over all segments to determine total volume of recharge. This volume is added to the volume previously in storage. The method used to estimate section outflow depends on the elevation of the water table at the divide, h_1. Thus, the value of h_1 corresponding to the new storage volume must be determined. For both the parallel and converging flow cases, there is no direct solution available for h_1 as a function of section volume, so the value of h_1 must be determined by an iterative scheme.

Drainage Phase

Liong et al. (1982) used a simple regression model calibrated against output from the Freeze (1971) model to study the change in section outflow with time, as the aquifer responds to recharge. The technique demonstrated that both the flow recession and the decline in water table height at the divide could be predicted quite accurately as functions of dimensionless parameters based on watershed characteristics. We use this concept to predict the dimensionless decline in water table height from day to day for the parallel flow case, Δh_d*, which is $\Delta h_d/L$. Liong et al. found that

$$\Delta h_d* = \exp(-B_p t*) \quad (3)$$

where t* is tK_s/L, and B_p is a function of h_d. The independent variables within these dimensionless parameters are as referenced in figure 2, and t is the time interval. In equation 3, B_p is the rate of decline in head at the divide from day to day. A series of experiments were run using the Smith-Hebbert (1982) model to evaluate B_p. From these experiments, it was found that B_p could be adequately expressed as a linear function of h_d*, where the slope and intercept are functions of the dimensionless watershed parameters, h_s* (h_s/L) and n.

The linear expression for B_p is for a parallel flow situation, where the rate of change in head is proportional to the rate of change of section outflow. However, in the converging situation, this is not the case. The rate of change in section storage, and thus, section outflow, is proportional to the integral product of the section surface area and the change in head. To develop an expression for the converging flow situation, we assumed that the rate of decline from day to day, B_c, can be related to that of the parallel condition by

$$B_c = R_b B_p \quad (4)$$

where R_b is a multiplying factor. The Smith-Hebbert model was used to evaluate R_b. Based on a number of runs with various watershed configurations, a relationship was developed giving R_b as a function of θ, R, and r_o. Thus, B_c can be calculated directly from B_p. See Keiner (1983) for further discussion of the converging flow situation.

Using all of the above equations, we can calculate the head drop for both parallel and converging flow cases during a time interval, given h_s, h_d, n, K_s, L or R, r_o, and θ.

Volume of Discharge

Having determined the head at the divide at the end of the day as a function of the head after recharge, discharge to the channel during the time interval is assumed equal to the change in storage volume during the drainage phase. The storage change is calculated as storativity multiplied by the difference between integrations of the profiles (equation 1 or 2) after recharge and after drainage respectively. The above procedures are applied repeatedly from day to day to simulate the time-varying volumes of water discharged to the stream channel from all representative flow paths comprising the watershed, and the simulated channel inflows are passed to the channel routing subroutine of SWAM.

Application

The model was applied to a small grassland watershed, No. 5142, near Chickasha, OK. Twenty-nine flow sections were used to represent the 145-ha watershed; the length of channel receiving ground-water contribution was determined by field observation. Observation wells near the divide indicated that the ground-water levels were approximately 3.0 to 4.6 m above the channel. Based on these observations, the height of the water table at the divide above the channel elevation was assumed proportional to the length of the flow path, with the longest path having a head of 4.6 m. Depth of the zone contributing water to the channel, h_s, was estimated at 5.2 m; storativity was very low, estimated at 0.002. A long-duration flowrate of 2.8×10^{-4} m^3/s from watershed records was converted to a steady-state recharge of 1.66×10^{-5} m/day to set initial conditions. Since the objective of this simulation was simply to demonstrate the performance of the ground-water model, recharge rates and durations were estimated from flow records on the watershed. Results of the simulation, using these inputs and making no adjustments to the watershed parameters, are shown in figure 3.

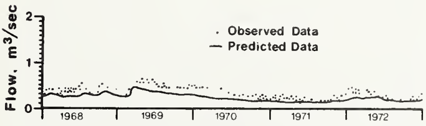

Figure 3.--Ground-water flow on Watershed 5142 near Chickasha, OK.

Concentration Modeling

The model also simulates concentration of dissolved, conservative chemicals in the ground-water discharge to the stream as well as within the ground-water body itself. Whereas the flow simulation lumps recharge, effectively neglecting partitions within the section resulting from spatially variable recharge rates or concentrations, the water quality routine is based on individual partition characteristics.

A mass balance of water is calculated for each partition on a daily basis, including flow exchange between partitions. The mass balance reflects the actual amount of recharge occurring upslope of each partition. The water balance operates between beginning and ending water surface profiles of a time step; the intermediate water table position of the flow model (after recharge) is neglected. The difference between beginning and ending volumes of water within a partition for a given day is calculated by integrating equation 1 or 2 between partition boundaries. Change of storage, which can be either positive or negative, must equal the sum of the inflows and outflows during the same day; that is, the recharge added to the partition, plus inflow to the partition from the next partition upslope, minus partition outflow to the next partition downslope.

Considering the most upslope partition first, as shown in figure 4, the only input is recharge; thus, change in saturated volume within the partition during a time step must equal recharge minus partition outflow. Volume of recharge to the partition is calculated using the actual recharge rate, i_1, and the partition length. Since change in storage is known, transfer of water to the next partition downslope, $qout_1$, may be calculated directly. A similar water balance can now be done for partition 2, except its inflow from upslope is equal to the partition 1 outflow just calculated. Exchange of water between partitions calculated this way considers a combination of real water volumes (spatially varied recharge) and mathematical water volumes (resulting from the flow model water surface

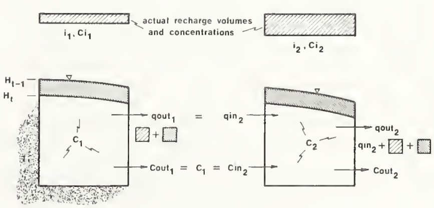

Figure 4.--Partition-based water balance for concentration simulation.

profile assumptions) reflecting the variable recharge rate over the watershed. The outcome of such flow routing is that ground water within the section will appear to move slower through zones which have little or no recharge upslope and faster through zones with the bulk of the recharge upslope.

This partition-based water balance provides the basis for chemical routing. Chemicals are also balanced within each partition by multiplying each flow component in the water balance by its respective concentration, with the partition concentration at the end of the time step being the unknown. By doing this, complete mixing within each partition and plug flow between partitions is inherently implied. To begin simulation, all partition concentrations must be initialized in a manner similar to the recharge rate and ground-water level in the flow portion of the model. Partition outflow concentration is set equal to the partition concentration itself, and solution for the partition's concentration at the end of each time step is calculated as (using partition 2 of fig. 4 as an example)

$$C_{2,t} = \frac{1}{Q_{2,t}} (Q_{2,t-1}\, C_{2,t-1} + i_{2,t}\, Ci_{2,t} + qout_{1,t}\, C_{1,t-1} - qout_{2,t}\, C_{2,t-1}) \quad (5)$$

where t represents the time step and Q is partition storage volume.

Equation 5 is a complete chemical mass balance within each partition for each time interval, since chemical concentrations are all directly associated with their transporting water. Concentration of the ground-water input to the stream is simply the last partition's concentration during each time step, while the within-partition concentrations reflect, to some extent, the distribution of recharge inputs to the section in both time and space.

No watershed water quality data has been used to test the model as yet; however, patterns of output concentration have been compared to calculated travel times for given section configurations. Figure 5 shows the ground-water concentration input to the stream for the four flux-concentration configurations shown; ground-water zones beneath the 100-p/m recharge input were initialized to 100 p/m. Equilibrium concentrations simulated at the outlet are as expected. A lag in response is seen, which depends on distance of the high concentration zone from the stream. Also shown on the figure are calculated travel times from the location of the initial chemical front to the stream. Travel times were determined by a numerical integration of the velocity distribution under the Dupuit-Forchheimer water table profile used in the flow model, equation 1. It can be seen that the travel times intersect the model responses consistently at about 60 percent of equilibrium concentration.

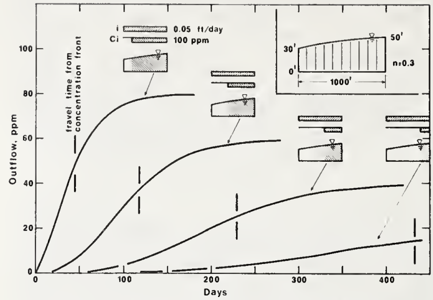

Figure 5.--Comparison of subsurface flow model response with analytic travel times.

Based on this and other mathematical testing, the ground-water-quality routine displays reasonable behavior. Chemical mass input by recharge is fully conserved, equilibrium output concentrations are as expected, and concentration response times correspond to calculated travel times. Further testing and application to field situations remain to be done so as to verify the response of the quality algorithms.

SUMMARY

In this paper, we describe the subsurface flow submodel of SWAM. The parameters of the model have been determined such that its simulated response is comparable to that of a complete finite-difference model of the same processes. Flow is visualized as consisting of parallel or converging paths contributing directly to the stream. The flow rate from any section is a function of section length, aquifer thickness at the stream, saturated hydraulic conductivity, storativity (effective porosity), a width representative of the flow path, and the angle of convergence. Simulation is based on a continuous accounting of volume of water in the saturated section, and equations predicting change in water level at the divide. Recharge to the water table adds directly to the storage volume and raises the water table level, while the outflow rate is calculated from the change in storage occurring during the drainage phase of the time interval. Provision is made to partition each flow section according to different land use zones over the section. This enables the model to simulate the concentration of dissolved constituents within the section and their movement to the stream channel. The hydrology portion of the model was demonstrated by application to a watershed in Oklahoma, while the water quality routine was illustrated by comparing its output to calculated travel times.

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CHEMICAL EFFECTS ON INFILTRATION

D.L. Suarez*

Most studies of soil-water infiltration have focused on control by soil physical properties, such as bulk density. In most instances infiltration experiments with rain simulators have been conducted with well or surface waters. Use of these waters may properly simulate infiltration under sprinkler irrigation (assuming the irrigation water is of comparable quality), but this may not be the case for rainfall. The infiltration process is significantly influenced by soil and water chemical properties. Since rain water differs from most irrigation waters, infiltration experiments not conducted with rain water may be misleading with respect to the infiltration and runoff to be expected under natural rainfall conditions.

The various chemical processes which interact with the soil physical properties to reduce infiltration are most important when dilute waters are used. One of the most important processes is the dispersion of clay particles. Cation substitution in the structure of clays results in negatively charged surfaces. Oppositely charged ions in the surrounding "double layer" solution neutralize the surface charge. The thickness of the double layer is dependent on the concentration and valence of the ion in solution. Figure 1 shows the theoretical relationship between concentration and double layer thickness for montmorillonite (after van Olphen 1967) based on electrostatic considerations. Rain water is almost always below 1 $mmol_c \cdot L^{-1}$ and usually below 0.3 $mmol_c \cdot L^{-1}$, (Hem 1970) in contrast with irrigation water, which is typically above 3 $mmmol_c \cdot L^{-1}$ in concentration. Thus surface soil clays in contact with rain rather than irrigation water will have an increased double layer thickness. The increased double layer thickness results in particle repulsion, which can result in movement of clay particles, blocking of pores, and thus reduced infiltration and crust formation. These processes are enhanced when the exchangeable ion is monovalent instead of divalent as also shown in figure 1. The double layer thickness for kaolinite shown in figure 2 (calculated from Marshall 1949) shows a concentration and cation charge effect similar to that of montmorillonite.

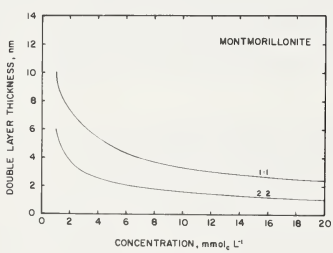

Figure 1.--Calculated double layer thickness of montmorillonite for 1:1 and 2:2 electrolytes as a function of solute concentration expressed as $mmol_c \cdot L^{-1}$. Data from van Olphen (1967).

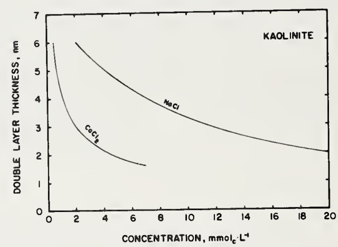

Figure 2.--Calculated double layer thickness of kaolinite for NaCl and $CaCl_2$ electrolytes as a function of solute concentration expressed as $mmol_c \cdot L^{-1}$. Data from Marshall (1949).

It has been shown that the hydraulic conductivity of a soil decreases as the exchangeable sodium percent (ESP) increases, once the solute concentration is below a critical value (Quirk and Schofield 1955). This is consistent with calculations of double layer thickness. Above the critical value no changes in hydraulic conductivity are likely to be observed, with changes in ESP or solute concentration; thus one could erroneously conclude that these chemical processes were un-important. In a laboratory column study, Frenkel et al. (1978) observed that there was a good relationship between reduction in hydraulic conductivity and clay movement, thus demonstrating the importance of dispersion.

Montmorillonites with Ca on the exchange sites form packets of clay platelets. With increasing ESP, sodium is preferentially adsorbed on the external surfaces. An increased double layer thickness develops around the tactoid, leading to

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potential dispersion of the packets before interlayer swelling occurs (Shainberg and Caiserman 1971). The actual sodium adsorption ratio (SAR) of the water, or soil ESP, and solute concentration at which dispersion can occur are dependent on many factors. Shown in figure 3 is the threshold line given by Rhoades (1982) for the more sensitive arid land soils. The dispersion hazard is usually expressed in terms of the irrigation water quality since the surface soil layers usually limit the infiltration rate and are most susceptable to crusting and dispersion. Values to the left of the line indicate that substantial reductions in infiltration are likely to occur; values to the right of the line indicate that use of those waters should not cause a problem. The X intercept is 0.3 $mmol_c \cdot L^{-1}$, indicating that even at SAR=0, rainfall is considered to potentially reduce infiltration due to dispersion.

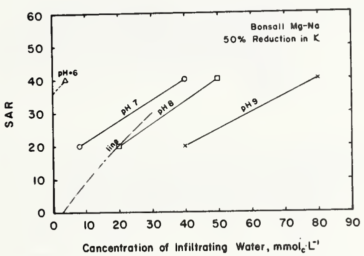

Figure 3. --Relationship between SAR and solute concentration for Bonsall soil when a 50 percent reduction in K occurred for pH 6, 7, 8, or 9 infiltrating solutions. Data calculated from Suarez et al. (1984). Also shown is the threshold line given by Rhoades (1982). Values to the left of the line indicate that substantial reductions in infiltration are likely to occur.

Although this threshold line provides a guideline, chemical factors other than the SAR and electrolyte concentration play an important role in effecting changes in infiltration rates. Also shown in figure 3 is the relationship between SAR and electrolyte concentration at which a 50 percent reduction in hydraulic conductivity (K) occurred, for various pH values (Suarez et al. 1984). These experiments were made with soil columns packed uniformly to a bulk density of 1.5. The infiltrating solutions were pumped at a constant flow rate of 17$\mu L \cdot s^{-1}$ into the 5.5-cm-ID columns with a peristaltic pump. Although the slopes of the lines are similar to the threshold line given by Rhoades (1982), they indicate that the reduction in K is very pH dependent, at least for Bonsall soil. Arlington soil in contrast had almost no pH dependence on K. That increasing pH has an adverse effect on K can be expected, due to charge reversal (from positive to negative charge) of the oxide minerals and edge charge reversal of the clay minerals with subsequent breaking of edge to face bonding.

Another important factor in determining adverse changes in K is the mineral weathering rate of a soil. As expected it is the actual soil solution composition, rather than the infiltrating water composition, that determines soil dispersion. For arid land soils this weathering rate can be a substantial factor. Bonsall soil was chosen for the pH study because the weathering rate was sufficiently slow that solution composition of the infiltrating water was the same as that for the effluent water. That the changes in K are very soil dependent is evident from figure 4 (from Shainberg et al. 1981). In this experiment soils were leached with distilled water at different initial ESP, and K was subsequently measured.

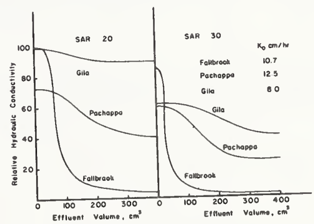

Figure 4. --Relative hydraulic conductivity versus effluent volume for Fallbrook, Pachappa, and Gila soils. Soils were equilibrated with SAR 20 and SAR 30 solutions then leached with distilled water (after Shainberg et al. 1981).

The lack of reduction in K for Gila soil despite its high initial sodicity is explainable if we consider soil weathering rates. Figure 5 shows that the column effluent electrical conductivity for the Gila soil did not drop below 0.3 $dS \cdot m^{-1}$. In contrast, the Pachappa soil had a larger reduction in K (fig. 4) and a lower effluent electrical conductivity (fig. 5) compared to Gila soil. Fallbrook soil had the lowest weathering rate as determined from the effluent electrical conductivity and, not surprisingly, the largest reduction in K.

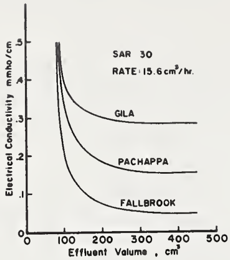

Figure 5. --Electrical conductivity of effluent solutions as a function of effluent volume for Fallbrook, Pachappa, and Gila soils leached with distilled water (after Shainberg et al. 1981).

Measurement of K is a very time consuming process, but predictions of when K will change due to dispersion can be made using other simple measurements. Figure 6 shows the relationship between SAR and solution concentration at which a 50 percent reduction in optical transmission occurred (data from Suarez et al. 1984). In these experiments soils were repeatedly reacted with solutions of the given SAR, concentration, and pH until equilibrated. Soil-water suspensions were shaken then allowed to settle for 22 hours. Changes in optical transmission thus represent clay dispersion. A comparison of figures 3 and 5 indicates that changes in optical transmission provide a good indicator of changes in K. Arora and Coleman (1979) reported flocculation values for Panoche, Hanford, and Ramona soils reacted with Ca-Na solutions. These values (fig. 7) show typical differences among soils.

Relationships between changes in hydraulic conductivity and other indicators of dispersion are also available. Hamid and Mustafa (1975) showed significant linear relationships (r^2 values of 0.81 and 0.89) between relative hydraulic conductivity and a dispersion index. Their dispersion index was obtained by pipette measurements of the clay and silt fraction of the soil when the soil was reacted with waters of differing ESP and concentration. Since different regression lines were obtained, however, this method requires that the K vs. dispersion index be established for each soil. Other factors have been shown to affect aggregate stability, including organic content or nitrogen and iron oxide content. Dong et al. (1983) described a dispersibility measurement to simulate natural water erosion and particle transport. The ratio of the amount of

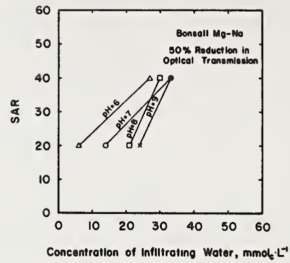

Figure 6. --Values of SAR and solute concentration at which a 50 percent reduction in optical transmission occurs from Bonsall soil at pH 6, 7, 8, and 9. Data from Suarez et al. (1984).

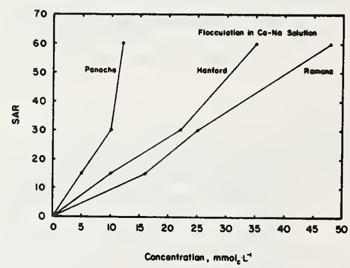

Figure 7. --Flocculation values for Panoche, Hanford, and Ramona soils as a function of SAR and solute concentration. Data from Arora and Coleman (1979).

clay-sized material released by shaking a 1:10 weight/volume soil water mixture to the amount obtained after ultrasound treatment was called the clay dispersibility ratio. This ratio was inversely related to organic carbon content.

Similarly in an extensive study, Kemper and Koch (1966) developed a measure of aggregate stability by wet sieving preceded by saturation under vacuum. Based on measurements with over 500 soil samples, they established high correlations between aggregate stability and percent nitrogen (or organic matter shown in fig. 8) and aggregate stability and iron oxide content (shown in fig. 9).

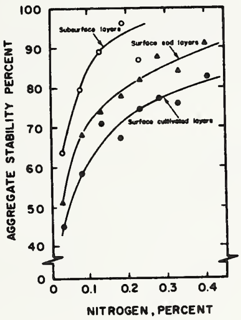

Figure 8. --Relationship between aggregate stability and nitrogen percent for surface and subsurface soil layers (after Kemper and Koch 1966).

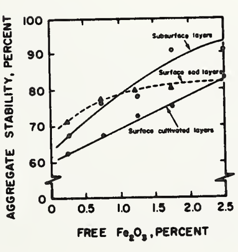

Figure 9. --Relationship between aggregate stability and free Fe_2O_3 percent for surface and subsurface soil layers (after Kemper and Koch 1966).

The data also indicate that surface cultivated layers have lower aggregate stability than surface sod or subsurface layers. It might be expected that soils with higher aggregate stability would be less susceptable to dispersion caused by the chemical processes discussed; however, this has not been established. Since changes in aggregate stability have been correlated to changes in hydraulic conductivity, it appears worthwhile to examine the relationship between the variables (such as exchangeable sodium and pH) which cause changes in aggregate stability and dispersion, and the soil properties (such as nitrogen and iron oxide content) which are correlated to aggregate stability.

Predictive relationships for infiltration need to consider the chemical processes which cause dispersion, particularly for dilute irrigation waters or rainfall. Dispersion and reductions in hydraulic conductivity have been shown to be dependent on exchangeable sodium, solute concentration, and pH. The critical salt concentration, ESP, and pH values at which dispersion and reduction in hydraulic conductivity occur are soil dependent but in a manner which is not presently predictable. Until these variables are better characterized, the correlations between dispersion or changes in aggregate stability and hydraulic conductivity are sufficient such that they can usually be used to predict changes in hydraulic conductivity. Use of these correlations reduces the need for time consuming hydraulic conductivity studies.

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EROSION AND SEDIMENTATION - SCS OVERVIEW

Dennie G. Burns[1]

I am very impressed with the progress of scientists in the Agricultural Research Service (ARS) in developing computer models needed to answer some very difficult technical questions about erosion and sedimentation. It is a real challenge for SCS program managers and technical personnel to keep up with the progress and to adapt those tools to the day-to-day delivery of services. I appreciate the opportunity to give you my thoughts on how computer models might help the Soil Conservation Service (SCS) further in managing programs to control erosion and sedimentation.

In my opinion, many of the questions SCS faces in implementing the National Conservation Program (NCP) can only be answered through judgment based on analyses by computer models. You have heard a lot of discussion in connection with the NCP about redirection, targeting, evaluation and analysis, priority setting, pilot projects--all designed to increase the effectiveness with which USDA delivers its services. Those discussions nearly always lead to three very basic questions:

1. What level, or degree, of land treatment is necessary to sustain agricultural productivity?

2. What mix of incentives (technical assistance, financial assistance, information and education) will most efficiently cause that treatment to be carried out?

3. Where financial assistance is necessary, what level of Federal cost sharing is appropriate.

LEVEL OF TREATMENT

In SCS, we plan systems of conservation practices that will reduce the erosion rate to the level at or below which the soil will continue to produce food and fiber indefinitely and economically. We call this level of erosion the soil loss tolerance (T) value. The T values SCS uses for soils in the United States range to a maximum of 5 tons per acre per year, as established in the early 1960's on the best data and judgment then available. We measure our agency's progress partly in terms of "land adequately protected," which means erosion reduced at least to T value; and we spend a lot of public funds helping farmers and ranchers get to that level.

How defensible is our measure of success, that is, how defensible are the T values? Is reduction of erosion to an average of 5 tons per acre per year or 3 tons per acre per year truly adequate? Many say those values and our policy are too restrictive, others say our goals are too low and allow too much deterioration. Who is right?

Right now--today--we need a model that reliably can predict for every soil in the country how much basic potential (unmasked by technology) there is for producing food and fiber we loose, per unit of input, at various erosion rates. To avoid untimely, uneconomic investments in resource management systems, we need to be able to establish, for each soil, an allowable erosion rate based on an accepted level of risk. That level of risk needs to be closely related to our level of confidence, or lack of it, in future technological development associated with erosion control and food and fiber production. That model or set of models needs to be able to say--given the assumptions or decisions about an acceptable level of risk--"Here is the allowable erosion rate associated with that decision." With that kind of answer we could judge the defensibility of our recommendations for land treatment and modify them where appropriate.

I hope that future generations of such models as the Erosion Productivity Impact Calculator (EPIC) will allow us to determine soil loss tolerance more accurately.

MIX OF INCENTIVES

The USDA provides three incentives intended to motivate farmers and ranchers to voluntarily apply conservation systems. They are financial assistance (cost sharing, loans, and so forth), technical assistance (planning, design, layout, followup), and information and education. Under some circumstances, either a good information and education program or technical assistance, alone, may get the job done; but, generally, there is an optimum mix of incentives. Unfortunately, our tendency is to maximize each incentive and see if that works. My contention is that in doing so, we spend more Federal funds than we need to.

We therefore need models that determine the best mix of incentives--particularly in our project and targeting activities under NCP.

LEVEL OF COST SHARING

I believe there are three reasons for USDA and the public to share the cost of applying conservation systems:

1. The benefits accrue to the public (offsite).

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2. The benefits accrue beyond the planning horizon of the producer, perhaps to future generations.

3. The systems involve changes in management or applications of technology that need to be demonstrated to the producers in the target area (incentive payments).

Even these few reasons are not without challenge. Many would apply a parallel to the polluter-should-pay concept to conservation. Others would contend that there are better ways to ensure future ability to meet food and fiber needs than spending large amounts of public funds on conservation. To accurately calculate the amount of Federal funding for these three reasons I have given, we need good analytic tools, including computer models, soon.

1. We need to better quantify offsite damages, locate the cause of those damages, analyze alternative corrective measures, and evaluate the level of benefits that accrue to the landowner and public.

2. We need to do a better job of determining the rate of accrual of benefits and costs associated with both the public and private benefits and to agree on when private and onsite benefits become deferred and public benefits.

3. We need to do a better job of determining the minimum level of incentive payments needed to demonstrate technology and motivate farmers to assume higher levels of management.

4. We need to put all of these data on costs and benefits together for analysis in project areas and target areas, and even national analysis. We need to be able to determine cost-sharing rates for projects quickly and with less research.

CLOSING COMMENTS

That is my view of the big picture concerning SCS program managers' needs for soil and water conservation models. Some, I guess, would say that I ask for the impossible or, at least, that I am a little unreasonable. But others say that I cannot see the big picture and that I am a piker with my small thinking. I do not know. But I do know that the work scientists in ARS and technical specialists in SCS are doing is critical to insuring cost-effective soil and water conservation programs in the future.

We have come a long way. I am excited about the progress that has been made in soil and water conservation modeling, but I also think that we have just started. Do not be discouraged that program managers want you to do more than you can do without sacrificing scientific credibility. If what you are doing is good and worth doing, that will always be the case. It is when program managers are not interested in what you produce that you need to worry.

Keep up the outstanding work.

EROSION AND SEDIMENTATION -- SCS OVERVIEW

Douglas E. Hawkins[1]

We in SCS appreciate the opportunity to participate in this conference. Mr. John W. Peterson, Director, Project Development and Maintenance Division, who was scheduled to make these remarks, asked me to express his interest in the session and his regrets that he had to leave before the conference ended.

These comments are presented from a perspective of the SCS, Water Resource Program Manager. These programs represent 35 to 50 percent of SCS's annual budget.

Most of these programs are unique in that enabling legislation requires that project plans have benefits that exceed costs. The programs are influenced further by the U.S. Department of Agriculture (USDA), National Conservation Program (NCP) priorities.

These priorities are now the basis for making many program decisions. To support the Department's number one priority, erosion control, we are developing watershed projects for watershed protection only. Since 1980, 36 of these projects have been planned and funded. These plans emphasize land treatment for erosion, water conservation, and water quality rather than upstream flood reduction.

At the same time SCS was responding to the USDA, NCP priorities, the federal government's "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies" (Water Resources Council, 1983 for planning water resource projects were put into effect. These guidelines require that the selected plan be the alternative that maximizes net economic benefits, unless a Secretarial exception is granted.

SCS is evaluating watershed protection plans using similar procedures as used in the more conventional flood control projects. This results in trying to determine the national economic development component based on productivity. Planners know there are other considerations such as offsite effects, but many times do not have the tools to evaluate these effects.

Water resource projects, including watershed protection projects, are problem-objective oriented. Plan formulation requires complete problem definition, clearly stated objectives, and evaluating all benefits and effects of various alternatives. Planners need better evaluation tools to help with this task.

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Evaluation of all benefits/impacts of watershed protection projects is very difficult. Present techniques seem to do a good job handling the benefits/impacts associated with cropland erosion relating to loss of productivity. Evaluation techniques are needed for offsite impacts. Almost all land treatment systems contain components whose principal impacts are water disposal (terraces, diversion, waterways, and so forth) in addition to erosion control onsite.

Adequate data and evaluation tools are lacking to establish specific cause and effect relationships between land management activities and downstream water resource conditions. Water resource project planners have to answer many questions during plan development to the satisfaction of several critical reviewers. Better evaluation techniques are needed to help answer these questions.

Models that can help understand all impacts of land use changes are desperately needed. SCS needs tools that can be used by state and field office staffs. Program managers want these tools and are ready to pay for them. Policy regarding cost sharing in projects is not an issue that should keep us from understanding all the technical impacts of project plan alternatives. Models that simulate the cause and effect relationships between land use activities and water resource conditions on a watershed scale will help us gain this understanding.

Reference

U.S. Water Resources Council, Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies, the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 1983, p. 137.

EROSION PROCESSES-SCS ISSUES AND CONCERNS

Klaus W. Flach[1]

Improved modeling of source area processes is vital to SCS for the following reasons:

° For conservation planning: Soil conservationists working with farmers need credible models for recommending conservation alternatives.

° For setting national priorities: SCS needs models that allow equitable assessments of the magnitude of the erosion hazards in various parts of the country. This will enable SCS to target resoources to areas where they are needed most.

° For justifying expenditure of public funds: SCS needs credible models of erosion, the movement of erosion products, and the onsite as well as offsite effects of erosion to document national needs to USDA, OMB, and Congress.

Erosion models must address the real, three-dimensional world. We need to know where and how fast the soil erodes and where erosion products are deposited. We probably need to know during which season events of defined severity are likely to occur and how often they are likely to happen. And, we need to know whether and how often sediment will be deposited somewhere in the soil landscape where they may damage crops, and how often they may be deposited in streams or other bodies of water.

Models need to run with available data bases or with data that can be readily obtained. For the soil conservationist in the field, this means that he must be able to run them with information on soil maps and soil interpretation records; information he can obtain from the farmer; information on slope length, slope gradient, and microtopography that he can measure in the field; and topographical and weather information that he may obtain from USGS 7½-minute quadrangles and from applicable weather bureau records. Data available in digital form or data that may be obtained through remote sensing are preferable to data that require field work.

For regional and national use, models need to run on nationally available data bases or with data that can be obtained through automatic interpretation of remotely sensed resource information. Models used for regional or national assessment should be able to run on samples, such as those of the national assessment should be able to run on samples, such as those of the National Resources Inventory (NRI) and should include information on the sensitivity of the model to certain elements of input data so that SCS can decide how much it must spend collecting data to obtain information of a given reliability. It costs in excess of $100,000 to collect simple information on just one piece of land in each of the 3,400 soil conservation districts serviced by SCS. And, if a model requires information that is not in current data bases, SCS needs enough lead time to develop the technology and procedures to collect the information and to develop the necessary data base.

Models do not necessarily need to be simple. In a few years, SCS expects to have microcomputers in all of its field offices; hence, a reasonably complex model that runs on a micro will be satisfactory. But, as discussed before, inputs should be those that are available in an existing data base or should be reasonably easily obtainable preferably through other than field techniques. And, programs need to be user friendly.

In conclusion, it should be emphasized that models need to be developed jointly by the researcher and the user. Some of the tasks identified here are clearly the responsibility of the researcher and some are better done by the user. But, communication and cooperation are essential in all phases of the model development process.

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TRANSPORT AND DEPOSITION OF SEDIMENTS

W. H. Neibling and G. R. Foster[1]

INTRODUCTION

Only a fraction of sediment detached from source areas may be actually delivered to streams and lakes. The redistribution of sediment within a field-sized area is important in estimating the effect of erosion and deposition on productivity. The quantity and sizes of sediment leaving source areas are important when assessing the impact of erosion on downstream water quality and off-site damages from sedimentation. The ratio of sediment delivered to sediment produced, a delivery ratio, is dependent upon many factors that influence deposition of sediment enroute to receiving water bodies. Some of these factors include land use, slope shape, distance from source area to receiving body, number and arrangement of permanent flow channels, and presence of grassed waterways, terraces, or other control structures. To adequately model a process dependent on so many factors, we must first understand the physical processes of transport and deposition and then integrate knowledge of these processes into models that describe sediment movement over complex topography.

Runoff from source areas typically travels only a short distance as broad sheet flow. It then accumulates in rills or concentrated flow channels. Further downslope, land surfaces usually flatten and deposition begins, and the flow again becomes primarily broad sheet flow, with flow depths on the same order as the largest sediment size being transported. Therefore, broad, shallow flow concepts are generally appropriate for describing depositional processes, but even then the flow depth may be quite nonuniform across the slope.

Deposition of sediment occurs under a number of seemingly different conditions. The basic pocesses are the same, with differences due to scale and site-specific modifying influences. Large-scale deposition occurs at the base of slopes where transport capacity of the flow is insufficient to move all the sediment detached from the slope. This type of deposition is remote from the source area and covers a wide lateral area. Runoff is usually not uniformly distributed across the slope but enters the deposition region in a number of well-defined rills. Flow across the deposition area becomes more broad and shallow but still shows considerable variation in flow depth across the slope.

Deposition induced by tillage marks can occur in a number of ways. Deposition of sediment from rain-fed runoff in low-graded ridge and furrow systems occurs whenever the sediment load exceeds the transport capacity of the flow in the furrow. Deposition may also occur in the lower end of irrigation furrows. Sediment detached by high flow rates or steep grades deposits in the furrow as flow rate, and therefore transport capacity, decreases along the length of the furrow. Deposition may also occur in contour furrows on steep slopes, and in some cases even in up-and-down hill furrows. In the latter case, deposition occurs because the presence of ridges at short intervals prevents flow convergence. Runoff then occurs as low discharge flow in a large number of furrows. Small-scale deposition occurs in micro-depressions created by moldboard plow or some chisel operations. These depressions are quite effective in depositing sediment from surrounding contributing areas under low or moderate runoff conditions. High runoff rates may cause the depressional areas to overlap, interconnect and create flow paths downslope, removing some deposited sediment and transporting newly detached sediment.

Relatively little deposition or sediment transport research has been conducted for shallow flow conditions. Meyer et al. (1983) studied sediment transport in furrows typical of conditions in the Mississippi delta. Laboratory studies of various aspects of the transport process using glass beads (Meyer and Monke 1965), sand and coal (Davis et al. 1983), and eroded soil (Neibling and Foster 1983) and a field study by Young and Mutchler (1969) are examples of studies where flow conditions are similar to those observed in depositional areas. Some results from these studies conflict with the expected. For example, Davis et al. (1983) found that when using mixtures of large sand and small coal, the small coal deposited much easier than when using a large sand - large coal mixture. This unexpected enhancement of deposition of small sediment by the presence of larger sediment was also observed by Neibling and Foster (1983). Neibling and Foster also noted that in general, small eroded sediment deposited easier than expected and large, aggregated sediment particles were more easily transported than expected.

CURRENT MODELING APPROACHES

A number of methods are used to describe transport and deposition of sediment using average sediment characteristics, for example, average diameter and specific gravity. Typical of these methods is that of Li (1977), who used the Meyer-Peter Muller (1948) sediment transport equation for bedload and the Einstein (1950) method for suspended load. Typical models that consider transport and deposition of individual sediment classes are the CREAMS (USDA 1980) and ANSWERS (Dillaha and Beasley 1983) models. Both consider not only particle size but also particle density for each sediment size class. In ANSWERS, transport of all sediment larger than 10 μm is calculated by the Yalin (1963) bedload equation. Sediment smaller than 10 μm is considered washload and is transported whenever runoff is present. Deposition of sediment is considered on a class by

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class basis using five sediment classes with sizes ranging from <2 μm to >200 μm.

The transport/deposition section of CREAMS (Foster et al. 1981) uses the Yalin bedload equation to calculate transport of each of 20 or less individual sediment classes. Total transport is compared with the total load and any excess transport capacity is redistributed among classes deficient in transport capacity. The net result is to estimate less deposition than would be estimated without redistribution.

The literature shows that any one of several bedload or total load sediment transport equations have been satisfactory for estimating total transport and that some are better adapted to multiple-particle-class transport than are others. Many commonly used transport equations can be written in terms of a single set of dimensionless variables (Alonso et al. 1981). The relative importance of each variable depends on the flow asumptions and data sets used to derive the equation. None are entirely satisfactory for agricultural situations, especially for calculating transport capacity of mixtures having a wide range of particle sizes and densities. In fact, clearly some are highly unsatisfactory, which is not surprising since all are streamflow equations adapted to shallow flow, where conditions differ greatly from those used to develop the equations. Adequate prediction of transport by shallow flow with sediment diameter on the order of flow depth, low density soil aggregates, and spatially nonuniform runoff and sediment supplies requires distortion of parameter values with no rational method for a-priori parameter value selection.

Limitations of Current Approaches

One condition that is difficult to model, regardless of the method used, is spatial variation in water depth. Most current erosion models use an estimate of some "average" or "characteristic" depth to describe flow conditions. In practice, flow usually moves as broad sheet flow for a short distance and then enters a small channel. Small channels may or may not join to form larger channels as the flow moves downslope. On sloping land, ridges or other tillage-induced roughness may prevent downslope flow. As the slope flattens to the point where deposition occurs, the flow and sediment are not uniformly distributed across the slope but enter the deposition area as concentrated flow at a number of points. Typically, parameter values are adjusted, usually out of the normal range, to reasonably describe the observed deposition patterns. Surface roughness and local changes in topography (slope) also exhibit considerable spatial variation.

One condition not adequately considered in most current models is the relatively uniform lateral addition of sediment to concentrated flow. An example is low gradient, ridged fields, where sediment eroded from row side slopes moves downslope and enters an area of concentrated flow in the furrow area between rows. In some cases the flow is capable of transporting all the sediment eroded from the row sideslopes but actually transports only a fraction of the supply because sediment enters from the side, at the point in the flow where the shear stress is lowest. The net result is deposition of sediment at the edge of concentrated flow, with possible scour occurring in the center of the flow area, where shear stress is sufficient to transport all sediment in the flow and initiate scour.

Transport/Deposition Equations

The continuity equation for sediment routing as stated by Bennett (1974) contains components describing unsteady flow, sediment production or deposition, sediment transport downslope, and a dispersion term which accounts for the delay in settling of very fine particles with low fall velocities. Consideration of all these factors is often not practical for erosion modeling. Some simplification is thus required.

Neglecting the dispersion term simplifies computations. If the transport capacity of the flow changes, its sediment load is assumed to react immediately, with deposition of any load in excess of transport capacity. This approach is common for deposition of bedload and suspended load in channels where dispersion in the suspended load zone is negligible in comparison to vertical transfer due to storage in the bed. Meyer and Wischmeier (1969) also used this approach in an upland erosion model. This approach may be satisfactory for channel flow but not for shallow flow over cohesive soils. Laboratory and field observations indicate that the surface of deposited, cohesive, graded sediment is well defined, with very little interchange of sediment between previously deposited sediment and bedload. Under these conditions, both the sediment stored in the entire profile and the time required for particles of low fall velocity to reach the channel bottom are of importance.

Foster and Meyer (1975) proposed a first-order reaction equation to account for the time lag effect due to settling:

$$D = \alpha(t - g) \qquad [1]$$

where D = deposition (erosion) rate, mass per unit width per unit time
α = reaction coefficient, length^{-1},
t = transport capacity, mass per unit width per unit time, and
g = sediment load, mass per unit width per unit time.

The reaction coefficient (α) describes the relative ability of the flow to deposit sediment. During deposition simulations using equations 1 and 2, Davis (1978) found that α varied from 3 (easily transported) to 33/m (sediment that settles out of the flow quickly). Current work (Neibling and Foster 1983) suggests that α is also a function of rainfall rate, with α decreasing as rainfall rate (and therefore turbulence and reduced settling) increases.

Laboratory Observations

Deposition studies of eroded sediment on a concave laboratory bed under varying rates of sediment inflow, rainfall, and baseflow gave results that were not compatible with existing transport theory (Neibling and Foster 1983). Application of equations 1 and 2 and widely used sediment transport equations predict that as flow moves down a concave slope, the larger, (and/or more dense) difficult to transport sediment deposits first, with increasingly smaller sediment depositing as the slope flattens and transport capacity is reduced. In laboratory tests, however, the upslope edge of deposition was always composed of small , approximately 35- to 125- μm aggregates and primary particles and large, angular 2- to 8-mm primary particles. Since the typical height of roughness elements was very low, the moderately sized (125 μm to 8 mm) aggregates rolled downslope and deposited as the downslope edge of deposition advanced downslope. This pattern of deposition suggests a strong influence of both particle shape and particle density on the transport process.

In shallow (<1- to 5- mm depth) flows, the presence of rainfall aided downslope movement of all sizes of sediment. The surface profile of the deposited sediment reached equilibrium more quickly with rainfall, final slope was lower, and the upper edge of deposition was further downslope.

Preliminary analyses indicate that without rainfall, approximately one-third of the 2- to 10- μm sediment supplied to the test section is deposited, and for rainfall conditions, approximately one-fifth of the 2- to 10- μm supplied sediment is deposited. Even a larger percentage of the 10- to 35- μm supplied sediment is deposited for both rain and no-rain conditions. This result is in contrast to assumptions made in several models that small-sized, washload sediment is transported whenever runoff is present. It also suggests that plant canopy, and to some degree, crop residues that shield the surface from raindrop impact, may enhance deposition of fine sediment.

Meyer et al. (1983) evaluated transport of sediment along crop row furrows typical of Mississippi delta conditions using a parabolic laboratory channel. Of the factors studied, furrow gradient most significantly affected sediment transport capacity, with rates 10 to 100 times greater at 1 percent than at 0.2 percent slope, and generally more than 1,000 times as great at 5 percent as at 0.2 percent slope. Increasing flow rate and decreasing particle size both increased transport capacity but had much less effect than did gradient. In contrast with the results of Neibling and Foster, Meyer et al. found that the effect of rainfall on transport of well-graded sand was minor.

FUTURE RESEARCH NEEDS

Discrepancies between existing theory and experimental results suggest several areas requiring additional research. Better knowledge of sediment properties; derivation of transport relationships based on broad, shallow, flow conditions; and improved methods of considering spatial variablility of hydraulic and hydrologic variables should allow model results to more closely fit observed deposition and sediment yield data.

Sediment Properties

Models that separate eroded sediment into a number of size and density classes for sediment routing procedures require estimates of the sediment size distribution of the eroded material; the characteristic density of each size fraction; and, in some cases, the percentage of each fraction composed of sand, silt, and clay. Additional data on the size and density distribution of eroded sediment from different soils will be useful for both direct model input and as part of an enlarged data base for refinement of methods to predict sediment distributions proposed by Rhoton et al. (1982) and Foster et al. (1982). Additional data on the percentage of a given class of sediment composed of aggregates as opposed to primary particles are also needed.

The importance of particle density in computing deposition and transport has often been overlooked. Davis et al. (1983) noted significant density effects when comparing deposition patterns using sand ($\rho = 2.65$) and coal ($\rho = 1.67$). Rhoton et al. (1983) and Young (R. A. Young, USDA-ARS Morris, MN, personal communication) developed laboratory procedures to measure the density of sediment particles. Additional work to extend these methods to a broad range of soils, development of other methods of obtaining aggregate density, and a method of quantifying aggregate density are needed. Characterization of aggregate density over a range of sizes for a number of soils will provide needed information for erosion/deposition models.

Particle shape is an important factor in transport of sediment by shallow flow. We routinely observe soil aggregates of a given size rolling the complete length of the deposition area before depositing while primary particles of the same size are deposited at the upslope edge of deposition. The primary particles are angular and move downslope by sliding. Much more data are needed before particle shape can be described, given particle size and soil type or other soil characteristics.

Improved Basic Transport Relationships

Eventually, a transport equation derived for shallow flow conditions and its characteristic sediment should be developed. Such an equation would improve estimates of total deposition, deposition of individual sediment classes, and sediment yield. Although data sets from experiments using sand, coal or other noncohesive material will be helpful in developing such an equation, our observations with sediment eroded from

cohesive soil suggest that the majority of data used to develop such an equation should be sediment eroded from a soil mass. Data from concave slope experiments are a start in assembling a data set suitable for development of such an equation. The capability to explicitly predict the transport capacity of individual size fractions and distribution of any excess capacity among different size fractions when working with graded sediment loads, should be an integral part of any new sediment transport equation.

Additional research is required to determine how to best simplify the continuity equation to make it useable in models without sacrificing predictive power. Equation 1 has been proposed as one method to consider the dispersion term in the continuity equation. Davis et al. (1983) found that equation 1 worked well for noncohesive 156- and 342- μm diameter sand and crushed anthracite coal and for sand-coal mixtures on a concave bed. However, current work (Neibling and Foster 1983) suggests that for poorly graded, fine sediment ($D_{50} \simeq 40$ μm) eroded from cohesive soil, either equation 1 may need some modification or a new relationship may need to be developed to adequately describe observed transport/deposition data.

Spatial Variation within Fields

Some method of considering the spatial variation of flow and associated sediment supply on transport within fields should be developed to adequately describe deposition and sediment discharge from single-storm events. This consideration is especially important if the effect of sediment re-distribution within fields on productivity is to be evaluated. To a degree, transport and deposition by both broad sheet flow and concentrated flow can be estimated provided the sediment and hydraulic inputs are given. However, a type of flow (broad sheet or concentrated) must be assumed before computations are made. A real challenge is to incorporate sufficient information about spatial variation in topography and about soil and crop characteristics to allow the model to determine where flow will be broad and shallow, where it will be ephemeral or concentrated, and how much sediment will be delivered to a given point by upslope detachment and transport.

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MODELING EROSION AND DEPOSITION

R. M. Khanbilvardi and A. S. Rogowski[1/]

INTRODUCTION

Recently, a renewed emphasis has been placed on estimation of soil loss from agricultural, rural, and urban areas. Correct prediction of erosion and sediment yield is needed to select best management practices, to control or minimize soil loss to preserve soil productivity, and to prevent excessive degradation of water quality. To forecast the outcome or correct the damage, it is important to know (or be able to predict) not only the total sediment yield but also the sediment source and likely location of depositional sites.

Numerous erosion prediction equations and simulation models have been developed to describe the process. The principal models in use today have been derived either empirically from regression analysis, or hydraulically from the fundamental processes of soil erosion. The Universal Soil Loss Equation (Wischmeier and Smith 1978) is the best known of the former, while a closed form soil erosion equation proposed by Foster and Meyer (1972) exemplifies the latter.

Soil loss from a watershed is the consequence of a complex natural process involving soil detachment, entrainment, transport, and deposition. The primary factors involved in these processes are landscape topography, soil characteristics, amount of cover and rainfall, as well as infiltration and runoff rates. These factors can change from season to season, from storm to storm, and even during a storm event. In addition, mathematical equations describing the detachment and sediment transport capacity are not compatible and cannot be readily combined into a single expression. Lumped equations such as the Universal Soil Loss Equation (USLE) and modified USLE (MUSLE) (Williams 1974) cannot produce consistently good results over a broad spectrum of conditions. Therefore, to simulate erosion process on an individual storm basis, a fundamentally based approach needs to be selected, with separate equations for detachment and sediment transport.

The purpose of the studies described here was to develop a mathematical model for evaluating erosion from a complex watershed using a two-dimensional analysis. Such model would use single storm values of rainfall and runoff to compute erosion and sediment transport for that storm. It would also use readily available data and could be run without calibration or collection of additional data to determine input parameter values. Figure 1 shows the schematic diagram of the model developed, while the following sections illustrate its application to a Hastings watershed in Nebraska.

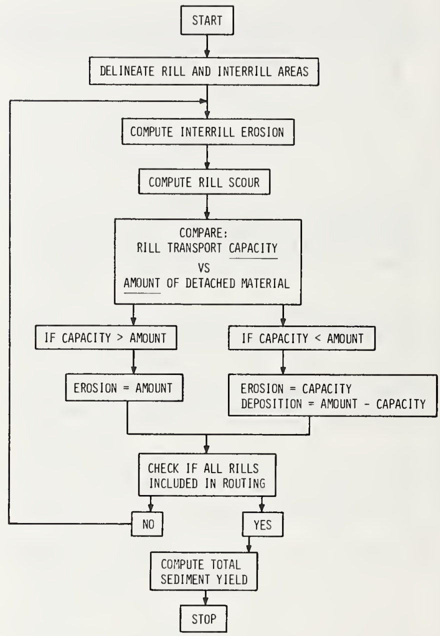

Figure 1.--Flow chart of the erosion-deposition model.

MODEL DESCRIPTION

In the model, a watershed, field, or plot is represented by a series of homogeneous, square, equal-size subareas. These can be as large or as small as need be. As a result, the site is divided into a grid represented by a node point in the center. The parameters at each node are assumed to be constant for a given subarea. Normally the model is set up on a 100- by 100-m grid (1 ha), but for simulator plots we have used grids as small as 0.6 m^2.

The model is based on the concept of dividing the erosion process into rill and interrill erosion. All the sediment detached from interrill areas is assumed to move laterally to the closest rills.

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Flows in rills transport this sediment as well as the sediment detached in the rills themselves (rill scour).

The governing equation of the erosion process known as the continuity equation derived by Foster and Meyer (1972) is used in the model. It is based on the assumption that sediment load is limited by either the amount of soil detachment or by sediment transport capacity.

After dividing the watershed into a grid of square subareas represented by node point in the center, the model computes cumulative infiltration at each node using Philip's (1957) infiltration equation. The parameters in Philip's equation, if not available experimentally, can be estimated from readily available data (Rogowski 1971, 1972).

The excess rainfall constitutes the overland flow component in the form of sheet or rill flow. The model, then, specifies the rill and interrill areas. For a given watershed condition, two factors seem to be highly important in this procedure: the size of subareas and hydrologic consideration of rainfall and runoff (Khanbilvardi et al. 1983a). In this procedure, the important rainfall characteristics are assumed to be known or available from stochastic generation.

The rill patterns which start at the rill sources and end at the area boundaries are then generated by computer. After delineating rill and interrill areas, the model specifies the interrill contributing areas. The interrill contributing areas are those portions of interrill areas which, according to partial area concept of hydrology, contribute detached soil material to rill areas. Sediment load from the interrill erosion on a contributing area is assumed to be transported into the closest rill by interrill sheet flow while USLE (Wischmeier and Smith 1978) is used to compute the soil detachment on interrill areas.

Eroded soil contributed from the interrill areas, along with the rill erosion component (rill scour), is then routed to the rill outlet. In order for detachment (rill scour) to occur in the rill, the flow shear stress must exceed the critical shear stress necessary for sediment transport (DuBoys 1879). This is believed to be the minimum requirement for initiation of sediment movement off the rill bed.

Once all the components have been computed, the standard routing procedure (Foster and Meyer 1972) is used to balance the amount of available eroded soil against rill flow transport capacity. Rill flow capacity, which accounts for the distribution of sediment between transport and deposition, is the controlling factor in this routing procedure. At each node the eroded soil from adjacent interrill areas plus the soil detached within the rill (rill scour) are compared with the rill flow transport capacity to determine the net amount of soil deposited or carried away from a given node. Rill transport capacity is computed from Yalin's (1963) transport equation, applied to concentrated shallow flow, in rills associated with upland erosion.

The model can predict the location and amount of erosion and deposition for individual storms over the entire watershed, as well as distribution of sediment load and potential stream inputs for any time after runoff has begun. As an added bonus, there is no need to use the sediment delivery ratio as a separate model parameter, since it is indirectly accounted for in the flow transport capacity and routing computations.

MODEL APPLICATION

To illustrate the model, several different size sites will be used. The model was originally applied to a small (1.4 ha) stripmined and reclaimed site in central Pennsylvania. Correlation between the predicted and measured values ($r = 0.88$) was encouraging and indicative of a satisfactory performance of the model in estimating areal distribution of erosion and deposition (Khanbilvardi et al. 1983b). The model was then applied to four small (3 x 10 m) plots with simulated rain. On the average, erosion and deposition as calculated by the model were in close agreement with erosion computed from experimental measurements to runoff and sediment yield (Rogowski et al. 1983, Jones 1983).

The original model was then modified (Khanbilvardi and Rogowski 1984) to cover a spectrum of conditions encountered on a watershed and applied to digitized data from a relatively large (600 ha) area; again the results were encouraging. It was at this time that we felt a need to verify the model on a good size (more than 100 ha) watershed especially in terms of total sediment yield. To do this and also to demonstrate the type of output information available, we chose for analysis the now closed W-5 (166 ha) USDA Hastings watershed in Nebraska, where extensive rainfall and sediment yield data have been collected during a 30 year period[2/]. Information on soil classification and texture, on moisture conditions, as well as on land use and on erosion control practices on this watershed were extracted from the site descriptions.

The model was run for a total of 30 storm events occurring in the period of 1957-65 at Hastings. The rainfall distribution observed for these storms closely followed type IIA SCS Storm classification. The watershed was then divided into square grid of 100- x 100-m subareas (1 ha each). After computing the runoff on each subarea, the model generated rill patterns and delineated contributing interrill areas.

Figure 2 compares the location of observed storm pathways (solid) and the predicted rill patterns (dashed) and indicates a generally good agreement between them. At the end of the model execution,

[2/] Osborn, H. B. and L. L. Kelly, 1974. A summary report of 30 years of hydrologic research. Unpublished report on the USDA Central Great Plains Experimental Watershed, Hastings, NE.

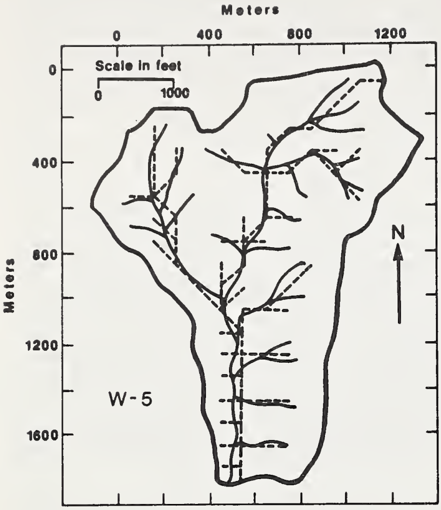

Figure 2.--Comparison of observed waterways (solid lines) and predicted rill pathways (dashed lines) for a selected storm (7-17-58).

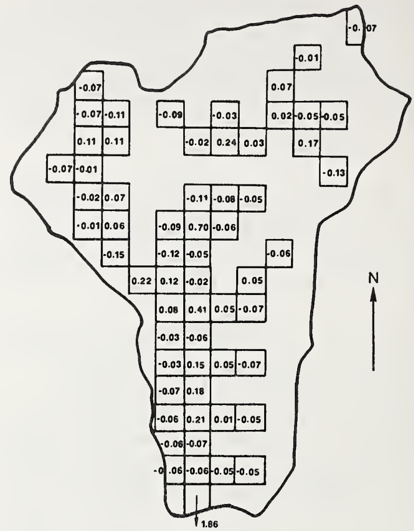

Figure 3.--Net amount (mm) of eroded soil removed (-) or deposited (+) on contributing areas at the end of selected storm.

net erosion or deposition at each subarea was determined. Figure 3 shows this areal distribution for a selected storm (17 July 1958), assuming the median particle size of 2 to 3 mm. The positive values represent the total amount of sediment deposited on the indicated subareas and include the component of interrill erosion from contributing areas and rill scour up to that subarea. The negative values indicate the predicted net amount of soil removed on the subarea. The difference between total deposition (sum of positive values) and total erosion (sum of negative values) is due to rill scour contribution, which is not shown in this figure.

To evaluate the model performance, we compared the predicted values of sediment yield for all storms with the measured values (fig. 4). Statistical analysis indicated a good correlation (r = 0.99).

Because of the nature of erosion, particle size distribution of eroded soil from rill and interrill areas may be different. Particle size and density of the eroding scil can influence the total amount of soil loss. Eroded soil on a watershed is usually a mixture of both the primary particles and larger aggregates. Relative distribution of the particles and aggregates in the entrained sediment is a function of soil properties, management practices, cover, rainfall and runoff characteristics. If the particle size is not known, the model will estimate it as an upper limit of the size distribution.

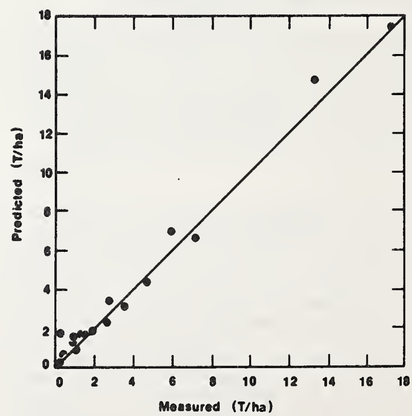

Figure 4.--Comparison of measured and predicted sediment loss from site.

SUMMARY AND CONCLUSIONS

An erosion-deposition model incorporating the fundamental erosion and sediment transport relationships on upland areas is described and illustrated. The model can be used on field- and plot-, as well as watershed-sized areas and can be applied to single storm events. It has potential for immediate application without the need for parameter calibration.

The model predicts patterns of sediment and water flow as well as the amounts of soil lost from interrill and rill areas on each subarea of the watershed. The subareas may be as large or as small as needed. The model determines the sediment sources and sinks and predicts distribution of materials detached by rainfall and rill scour.

To illustrate the application, the model was executed for 30 storm events on a watershed in Hastings, NE. The results indicated a general agreement between the predicted and observed water pathways on this watershed. The predicted sediment yield compared well with field measurements. Results obtained indicate that the model produces reasonable estimates of water pathways, erosion, and sediment yield from field-sized as well as plot- and watershed-sized areas and may prove to be a practical tool to analyze the influence of varying particle size distribution, role of sediment delivery ratio, and alternate management practices.

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A DYNAMIC EROSION CONCEPT

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WHAT'S DYNAMIC?

Estimating erosion with a dynamic concept implies calculating variables representing soil detachment, deposition, and transport processes at several points in space and time during each rainfall/runoff event. A dynamic erosion model is the solution of the unsteady continuity equation (Bennett 1974)

$$\partial G/\partial x + \partial(CA)/\partial t = D_f + D_i \qquad [1]$$

where G = sediment load in the flow (M/T),
x = distance along the slope (L),
C = concentration of the sediment in the flow, (M/L^3),
A = cross-sectional flow area (L^2),
t = time (T),
D_f = detachment or deposition by flow (M/T · L)
and D_i = lateral inflow of sediment, usually from detachment of sediment by raindrop impact or runoff from overland flow areas adjacent to channels (M/T · L)

Equation 1 is usually solved numerically in conjunction with a hydrology model that provides the needed hydrologic inputs (Smith 1976).

WHY DYNAMIC?

In addition to providing detail in time and space, dynamic erosion models provide increased accuracy. Empirical equations like the Universal Soil-Loss Equation (USLE) (Wischmeier and Smith 1978) lump basic erosion processes including detachment, deposition, and transport. For example, the effectiveness of ground cover in the USLE is frequently described by

$$\Phi_m = \exp(-bM) \qquad [2]$$

where Φ_m = mulch factor,
b = a coefficient,
and M = percent ground cover.

A typical value for b is 0.035 (Laflen et al. 1984), but experimentally, it has varied from about 1 to 10 (Laflen et al. 1981), apparently because of differences in rill erosion relative to interrill erosion and amount of deposition behind mulch pieces (Brenneman and Laflen 1982). Dynamic models by considering rill and interrill erosion and deposition separately more accurately describe the effect of mulch than can lumped models using equation 2. Moreover, accuracy is improved when the interaction of interrill erosion, rill erosion, and deposition with sediment transport capacity are considered throughout a storm. Deposition may control soil loss during initial and final runoff stages for a storm, while detachment may control soil loss during middle periods. The dynamic option of CREAMS2 is a state-of-the-art example of a dynamic erosion model and is a powerful tool for estimating erosion. It is used in the following discussion to illustrate typical relationships from a dynamic erosion model.

FLOW SURFACE REPRESENTATION

Runoff on many fields is concentrated in many small channels and rivulets rather than being uniform across the surface, a typical assumption in erosion models. The assumption of broad sheetflow distorts model parameters, leading to reduced transferability of a model to a wide variety of situations and thus to inaccurate results. In fact this assumption prohibits even the most fundamentally based model from producing observed field results for variables such as sediment particle distribution where the result is directly affected by nonuniform flow across slope, even though a model may be perfectly accurate for ideal flow.

Such distortion and inaccuracy is greatly reduced in CREAMS2 by assuming that runoff is concentrated in tillage marks, farm equipment tracks, and row middles between ridges along the grade of these small channels. The ridge sideslopes are analyzed as interrill areas, and flow in the furrows is hydraulically analyzed as channel flow. Flow in these channels is assumed to follow the ridges and furrows around a hill until a low area is reached where breakover of the ridges occurs. Downslope flow and its erosion in these breakover areas is analyzed as concentrated flow. When tillage implements like a moldboard plow do not leave defined ridges and furrows to contain and direct the runoff, runoff is assumed to move directly downslope.

EROSION SUBPROCESSES

Interrill Erosion

Interrill erosion is primarily caused by raindrop impact and thin flow on row sideslopes, on soil clods protruding above the water level, and on the nearly level interrill areas between rills. The interrill erosion equation used in CREAMS2 is (Foster 1982)

$$D_i = 0.0138\ K\ i_e^2[2.96(\sin\theta)^{0.79} + 0.56]\Phi_i, \qquad [3]$$

where D_i = interrill erosion rate ($kg/m^2 \cdot h$),
K = USLE soil erodibility factor ($kg \cdot h/N \cdot m^2$),
i_e = effective rainfall intensity (mm/h),
θ = slope angle of interrill area,
and Φ_i = soil loss ratio for interrill erosion.

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The effective intensity i_e accounts for rainfall intercepted by canopy, the diameter of reformed water drops falling from the canopy, and their impact velocity. The soil loss ratio Φ_i accounts for ground cover by crop residue, mulch, and ponded water and for cropping-management's alteration of soil erodibility from that represented by the USLE K factor.

Rill Erosion and Deposition

Rill erosion and deposition, both flow processes, are considered together, and the only mathematical difference between them is that deposition is negative (it reduces the sediment load) and detachment is positive (it adds to the sediment load). The equation in CREAMS2 for these processes is

$$D_r = \alpha(T_c - g) \qquad [4]$$

where D_r = detachment or deposition by flow $(M/T \cdot L^2)$,
α = a reaction coefficient (L^{-1}),
T_c = transport capacity of the flow per unit width $(M/T \cdot L)$,
and g = sediment load per unit width transported by the flow $(M/T \cdot L)$.

For detachment, the reaction coefficient α is given by

$$\alpha = D_c/T_c, \qquad [5]$$

where D_c = detachment capacity of the flow $(M/T \cdot l^2)$.

For deposition, α is given by

$$\alpha = \beta\, V_f/q, \qquad [6]$$

where β = a turbulence factor (e.g., large for shallow flow disturbed by raindrops),
V_f = fall velocity of sediment particle (L/T),
and q = discharge rate per unit width (L^2/T).

Both D_c and T_c are approximated by (Foster and Meyer 1975)

$$D_c = a_D\, \tau_s^{3/2} \qquad [7]$$

$$T_c = a_T\, \tau_s^{3/2}, \qquad [8]$$

where a_D = detachment capacity coefficient $(LM/F^{3/2})$,
a_T = transport capacity coefficient $(L^2M/F^{3/2})$,
and τ_s = shear stress of flow acting on the (F/L^2),

Sediment transport and hydraulic theory is used to divide flow's total shear into that acting on ground cover and roughness elements and that acting on the soil, τ_s, the part assumed to be responsible for detachment and sediment transport.

The coefficient a_D is estimated from (Foster 1982)

$$a_D = 139\ K\ \Phi_r, \qquad [9]$$

where Φ_r = a soil loss ratio for rill erosion
τ_s has units of N/m^2,
and D_c has units of $kg/m^2 \cdot h$.

The coefficient Φ_r describes the effects of buried residue and cropping-management on soil erodibility.

The coefficient a_T is estimated from Hussein's (1982) result of fitting equation 8 to the Yalin (1963) sediment transport equation

$$a_T = 188 - 468 f_c + 907\, f_c^2, \quad f_c < 0.22, \qquad [10]$$

$$a_T = 130, \quad f_c \geq 0.22, \qquad [11]$$

where f_c = fraction of clay in the soil,
τ_s has units of N/m^2,
T_c has units of $kg/m \cdot h$,
and D_c has units of $kg/m^2 \cdot h$.

Concentrated Flow Erosion

The topography of most fields causes overland flow to collect in a few major natural waterways before leaving a field. These depressions are usually tilled across, and, immediately following tillage, they may be quite susceptible to erosion. This erosion is sometimes as great as, or greater than, sheet and rill erosion for the field (Foster and Lane 1983). When erosion in concentrated flow areas is severe, grassed waterways or terraces and outlet channels are installed to safely convey runoff from the field at nonerosive velocities.

Erosion by concentrated flow is described in CREAMS2 by the equation

$$D_f = K_f(\tau_s - \tau_c), \qquad [12]$$

where D_f = detachment rate in concentrated flow,
K_f = soil erodibility factor for concentrated flow (M/F),
τ_s = shear stress of flow acting on channel boundary (F/L^2),
and τ_c = critical shear stress of soil (F/L^2).

CREAMS2 tracks the evolution of concentrated flow channels and models the reduction in erosion after a concentrated flow channel erodes to relatively nonerodible soil below the tilled zone.

Deposition in Small Impoundments

Deposition in small impoundments like tile outlet terraces is modeled using concepts from Laflen et al. (1978), which consider how likely a sediment particle is to settle to the bottom of the impoundment before being drawn through the outlet in the discharge water. The modeling equations for this deposition process are based on simple settling theory, and they simulate deposition during both the time varying inflow and the long period following the storm as an impoundment drains.

SEDIMENT CHARACTERISTICS

Sediment characteristics along with flow hydraulics determine sediment transport capacity and deposition rates. Deposition obviously reduces sediment load, but in the process, it enriches the sediment load in fines. Since most soil-adsorbed chemicals are associated with the fines, deposition's percent reduction of the chemical load on sediment is less than its percent reduction of sediment load. Deposition's selectivity therefore causes a chemical's concentration on sediment to be greater than its concentration in soil producing the sediment. This enrichment depends on sediment characteristics and how clay particles are distributed among aggregates in the sediment load. Clay is the most important soil particle for chemical transport because of its large surface area. Enrichment ratio based on specific surface area of sediment particles is computed directly in CREAMS2 as a function of the selectivity of deposition, which is also computed by CREAMS2.

Two options are available in CREAMS2 for describing sediment characteristics. One option permits the user to input diameter, density, composition, and specific surface area of particle constituents of each particle class. The second option is that sand, silt, and clay fractions of the soil are input and CREAMS2 computes the distribution of five particle classes: (1) primary clay, (2) primary silt, (3) small aggregate, (4) large aggregate, and (5) primary sand. Also, CREAMS2 computes the diameters and composition of the aggregate classes. Four characteristics-- diameter, density, aggregate composition, and distribution of particle classes-- are important for estimating transport of chemicals adsorbed on sediment. These sediment characteristics apply at the point of detachment of the sediment, and changes in sediment characteristics, including enrichment, are computed when deposition is calculated.

RESEARCH NEEDS

Clearly a better understanding of basic erosion, deposition, and sediment transport processes is needed for general improvement of dynamic erosion models. Obviously, research erosion models are needed to provide a base for developing future applied models. However, we are directing our statement of research needs to the specific requirements of dynamic erosion models for use by action agencies. Some of the major erosion modeling needs are given in the following paragraphs.

Use of Microtopography

Analysis of flow as it occurs nonuniformly across the ground surface reduces distortion in model parameters and improves model accuracy. Therefore, the flow at various cross sections must be described, which requires describing how erosion, deposition, consolidation, and tillage change flow cross sections. Furthermore, the "drainage net" of the rills and rivelets of flow must also be described as a function of slope, soil, tillage, cover, and time as it evolves. Roughness of the soil surface as it affects depression storage for deposited sediment and water cover to reduce the erosive forces of rainfall is important for rough soil surfaces following moldboard tillage and some other forms of primary tillage.

Watershed Representation

The problem of watershed representation is like the need to represent microtopography. Assumption of overland flow lengths of 2,000 m when the flow concentrates in waterways within 50 m distorts model parameter values and reduces accuracy. Creative and innovative ways of representing watersheds are needed to provide maximum spatial detail, maximum computational efficiency and accuracy, and minimal difficulty for the model user.

Parameter Evaluation

Parameter values that are functions of measureable properties of the field system are needed to apply models. Furthermore, models need to apply to the broad range of field conditions likely to be encountered by the user. Fundamental relationships for erosion processes have been developed by extensive modeling research. However, their power and effectiveness have been limited by adapting USLE factor values for parameters. Use of USLE values, which are lumped for rill and interrill erosion, sediment transport, and deposition, compromises model accuracy and applicability. Therefore, USLE parameter values should be laid aside, and experimental research conducted within the context of fundamental erosion processes to determine parameter values.

Soil Effects

Erosion modeling theory is developed for the mechanics of detachment, deposition, and sediment transport, especially by flow. However, relationships for soil erodibility effects remain empirical. Recent research (Al-Durrah and Bradford 1982) shows promise of relating soil erodibility to soil mechanical strength. Such research needs to accelerate to investigate how freezing and thawing, organic matter, tillage, and other factors affect soil strength in a way that can be described by broadly applicable equations.

Sediment Transport and Deposition

The relationships for detachment seem to be much better defined than those for sediment transport and deposition. Although much is known about sediment transport mechanics in stream channels, little of this knowledge is applicable to shallow overland flow as it occurs on fields. Improvements in sediment transport calculations also depend on improved flow hydraulic descriptions.

Hydrology

Accurate estimates of rainfall and runoff variables are required to drive dynamic erosion models. A dynamic erosion model requires spatially and temporally distributed data on

hydraulic conditions, which means having a rainfall hyetograph, an infiltration curve, and a function for interception and storage of rain on plants and in surface depressions as a part of the hydrology model. Stochastic climate generators are quite useful for driving these models, but rainstorm amounts must be dissaggregated into hyetographs. Parameters for hydrology models driving dynamic erosion models need to be closely related to soil, surface conditions, cropping, and management practices because the frequent purpose of erosion analyses is to evaluate how these factors affect erosion and how they might be modified to control erosion.

SUMMARY

Dynamic erosion models solve the unsteady continuity equation for mass transport of sediment; and, as a part of the solution, results include values for hydraulic and erosion conditions distributed in time and space. Fundamental erosion processes of detachment, transport, and deposition of sediment by rainfall and runoff are represented by dynamic erosion models. In addition to computing sediment load, these models compute sediment characteristics and how they are affected by deposition. Such capability is important for computing transport of sediment-borne chemicals. These models are driven by hydrology variables generated by a companion hydrology model. CREAMS2 represents state-of-the-art dynamic hydrology and erosion models.

While CREAMS2 can be used by action agencies, additional research is needed to further improve dynamic erosion models. For example, better descriptions of flow in microchannels would reduce distortion of model parameter values and improved accuracy. Parameter values determined from experiments based on fundamental erosion processes rather than adapting lumped parameter values from the Universal Soil Loss Equation would improve accuracy and extend applicability. Although much is known about sediment transport by stream flow, very little is known about sediment transport by overland flow. Finally, hydrology models need development and adaptation to the needs of erosion modeling.

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TILLAGE AND RESIDUE EFFECT ON EROSION FROM CROPLAND

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INTRODUCTION

Man has considerable impact on soil erosion through his use of tillage. An untilled soil, properly vegetated, can be virtually erosion free. In some areas, however, this doesn't suit man's purposes. Whenever cultivated crops are introduced, erosion usually increases.

Tillage is the mechanical manipulation of the soil so as to provide soil conditions favorable to the growth of crops--that is, to provide good soil tilth. One of the major effects of tillage is its effect on crop residue left on the soil surface after tillage and the distribution of crop residue through the soil profile. Other effects include surface roughness and porosity. Several questions relative to the effect of tillage and residue on erosion still exist. Is there an effect of tillage independent of residue? What are the interactions? How do we best quantify the effects? What research is needed and what approaches should be taken?

PRESENT TECHNOLOGY

The effects of tillage and residue on soil erosion are presently predicted using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). The basic technology for erosion prediction has changed little since the 1940s. The USLE, developed in the late 1950s and early 1960s, in many respects has not been changed as new practices have been developed; parameter values have been added to the initial parameter sets to reflect new and different practices.

A great deal of research has been directed toward the determination of these parameter values. Generally, this has involved the use of rainfall simulators and natural runoff plots to determine the ratio of soil loss with a given tillage and cropping system to soil loss from a conventional tillage system or from a fallow condition. Much of this work has been conducted since the last revision of the USLE (Wischmeier and Smith 1978) and these data are not included in current soil erosion predictions.

Laflen et al. (1981) related soil erosion to residue cover using the relationship

$$\text{Erosion} = A{*}EXP(-B{*}RC) \qquad (1)$$

where A and B are coefficients and RC is residue cover. Wischmeier (1973) defined a mulch factor (MF) as the ratio of soil erosion with residue cover to soil erosion without residue cover.

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Using equation 1, a soil erosion of A is predicted when residue cover is zero. Then, MF can be expressed as

$$MF = EXP(-B{*}RC) \qquad (2)$$

Laflen et al. (1981) reviewed available published data and found that B values in equation 2 ranged from 0.016 to 0.105. Laflen and Colvin (1981) also showed the variation of the mulch factor-residue cover relationships during a storm and how it changed differently for two different sites.

Only in the last several years have experiments been conducted that attempted to separate the effects of crop residue and the effects of tillage on soil erosion. Tillage can have a major effect, independently of residue cover, on soil erosion because tillage can incorporate residue and can create a rougher surface. The effects of tillage on surface runoff and soil erosion have been found to decrease as rainfall amounts increase (Baker and Laflen 1983).

Laflen et al. (1983) have presented an algebraic equation that computes the cropping-management factor (C) of the USLE directly. The equation is a subfactor approach similar to that of Wischmeier (1975) except that variables such as roughness, incorporated residue, residue cover, previous erosion, and time are quantified for their effect on soil erosion. The equation was developed specifically for use in individual storm soil loss estimates for modeling the impact of soil erosion on crop productivity. When this new algorithm is combined with a replacement for the rainfall factor that is more indicative of the hydrology for an individual storm, the USLE should be significantly improved for estimating individual storm soil erosion, and hence long-term annual soil erosion.

THE NEXT TECHNOLOGY

The next technology for erosion prediction will undoubtedly involve implementation of the rill-interrill concept for erosion prediction. Meyer and Wischmeier (1969) initially formulated such a model, while Foster et al. (1977) presented theory that makes such a model possible. Foster et al. (1981) implemented this theory in a simplified form in the CREAMS model (Knisel 1980). For successful implementation of the next technology, a considerable body of knowledge is required.

First, critical shear values and rill and interrill soil erodibilities must be estimated. Perhaps these can be estimated from a nomograph or from an equation. It is expected that the characteristics of the soil that affect critical shear and soil erodibility are changed by tillage. The exact relationships are unknown at this time; major studies are needed to develop these. For example, Laflen and Beasley (1960) have shown that critical shear was affected by bulk density, while Smerdon and Beasley (1961) showed that critical shear was related to a number of other soil properties that likely are little affected by tillage.

Another major issue is how to incorporate the effect of residue into the implementation of the rill-interrill concept. Hussein and Laflen (1982) related rill and interrill soil erodibility to crop residue cover. The disadvantage of an approach such as this is that these relationships are not universal; hence, many empirical studies would be required if such an approach were followed. Perhaps the approach by Foster et al. (1982) in assigning shear values to different portions of the bed should be followed. An additional complicating factor is that crop residue, at least in some conditions, could cause flow to become transport limiting (Brenneman and Laflen 1982).

Kramer and Meyer (1969) showed that runoff velocities were greatly reduced with only small amounts of residue. Brenneman and Laflen (1982) showed that sedimentation theory could be used to explain trapping of sediment above small pieces of residue. A rather simple analysis can demonstrate the potential effect of crop residue on soil erosion and the likelihood of significant interactions with other major variables. If it is assumed that all residue is round, it can be shown that the potential sediment storage (WS) in terms of weight per unit area per weight of residue is closely approxmated by

$$WS/WR = (1/2)(W_s/W_r)(1/S) \qquad (3)$$

where WR is residue weight per unit area, W_s and W_r are densities of the soil and residue, and S is land slope. In this analysis, all residue is assumed to be perpendicular to the slope and stores sediment as shown in figure 1. If the storage of sediment is how residue affects soil erosion, a major interaction can be expected between soil erosion, crop residue, and slope. The effectiveness of residue should also vary with soil characteristics that affect the size distribution of eroded soil.

The processes are very complicated. In some parts of a storm, at some locations and landscapes, deposition may be a major factor in erosion, while at other times or locations, it may be much less a factor. Models must be developed and used if we are to understand and quantify the potential interactions of soil, topography, residue, and tillage.

The next technology will also include a major

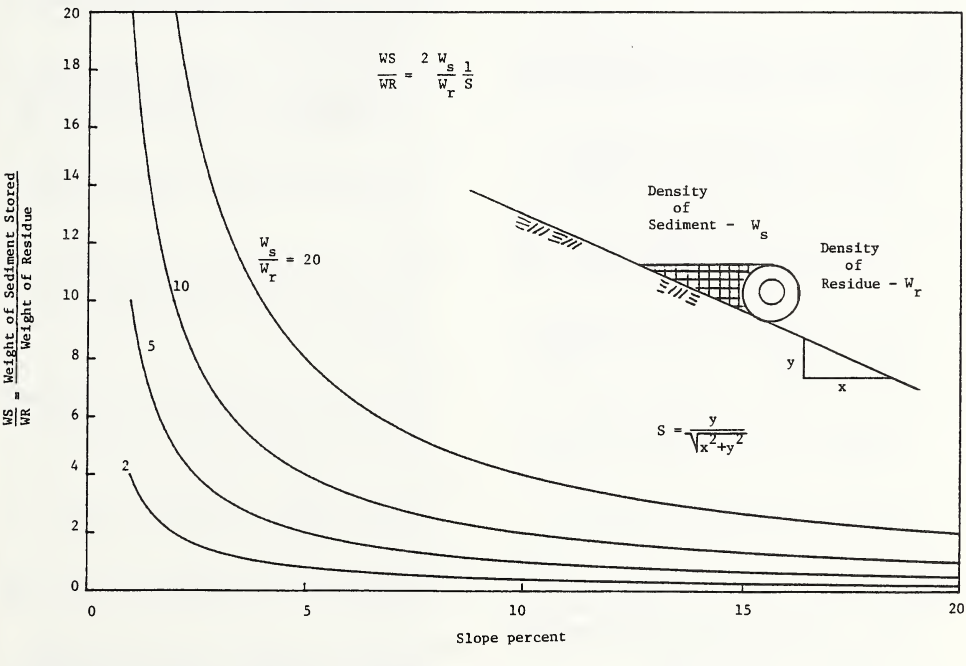

Figure 1. Maximum potential weight of sediment stored per unit weight of residue versus slope for several ratios of density of sediment to density of residue. Maximum based on all residue being circular, perpendicular to slope, and ponded volume full of deposited sediment.

component for estimating erosion from larger areas. To do this, erosion from channels will be predicted. While on a different scale than a rill, this is still a process of detachment and transport by flowing water and is part of the continuum from a very small rill to a major gully. However, the process of detachment is complicated because the channel may have sides and bottoms of different materials, and the hydraulics may be changing very rapidly in time and space. Knickpoints may develop, and the soil strength may be insufficient to maintain stable sides where undercutting occurs.

As with rill erosion, critical shear strength and channel erodibility must be related to soil properties. Controlled experiments must be conducted to determine these relationships, and these experiments must also reveal more about what processes are occurring with regard to bank failure, knickpoint hydraulics, and mass wastage. Additionally, we must describe these channel erosion processes as they relate to topographic factors if we are to model channel erosion. Eventually, we must determine how tillage and crop residue affect soil properties, flow paths, and flow amounts for good prediction of channel erosion.

SUMMARY

Major research needs in the area of determining tillage and residue effects on erosion from cropland include (not in any order of priority) the following:

1. improve our understanding of the effect of tillage on soil and surface properties. These properties would include residue distribution, surface roughness, and porosity.

2. for rill and interrill areas, better describe the effect of soil and surface properties on flow hydraulics and on the detachment, transport, and deposition of sediment.

3. relate critical shear and rill, interrill, and channel erodibilities to soil properties and determine how tillage and time affect these properties.

4. relate the erosion processes in small channels to soil and topographic factors and determine the effect of tillage on these factors.

5. determine effect of tillage on rill and channel location, slope, and shape.

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TEMPORAL CHANGES IN SOIL ERODIBILITY

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INTRODUCTION

The concept of soil erodibility as a constant value describing the response of the soil to a given erosivity has been satisfactory for long-term mean erosion prediction with the Univeral Soil Loss Equation (USLE) (Wischmeier and Smith 1978). Recent reexamination of soil loss data from continuous fallow plots (Mutchler and Carter 1983) has indicated that soil erodibility is not a constant, even for tilled plots without crop residue or live crop canopy to protect the soil from raindrop splash and to extract soil moisture. Soil erodibility is a dynamic property that varies with soil moisture, temperature, tillage, and biological and chemical factors. Satisfactory erosion prediction for individual events will require a dynamic response function for soil erodibility.

An approach to modeling the dynamic nature of soil erodibility would be to use a subfactor approach similar to the method currently used for determining C-factor values in the USLE (Laflen et al. 1983). This method should be capable of estimating the changes in soil erodibility for both types of erosive forces, that is, those relating to raindrop splash and to hydraulic forces of flowing water. Subfactors to be included should be those having the most effect on soil erodibility. In this paper, those subfactors thought to have the most influence are discussed, together with the research necessary to satisfy those needs.

CAUSES OF TEMPORAL CHANGES IN ERODIBILITY

Moisture and Temperature Effects

Moisture and temperature can significantly affect the resistance of soil to erosion. High soil moisture content in the surface layer can reduce resistance to erosion. In areas subject to soil freezing, high soil moisture can lead to formation of concrete frost which is generally impermeable. When soil with a concrete frost layer thaws from the surface, drainage is virtually nonexistent, and shear strength of the surface layer plummets. When the concrete layer thaws, the soil drains and shear strength is regained. This cycle occurs frequently in the Palouse Region of the Pacific Northwest because the soil may freeze and thaw many times during a winter. Should even small amounts of rain occur while the soil is thawing from the surface and a concrete frost layer is present, severe erosion results. In colder areas of the northern United States, the spring melt period is a time of high erosion hazard. However, in deep snow areas little soil loss results from spring snowmelt runoff alone. Most soil loss occurs as a result of rainfall or a combination of snowmelt and rainfall.

Freeze-thaw cycling generally leads to low bulk density of the surface soil (Pall et al. 1982). Conditions of low density and high moisture content provide a soil surface that is very susceptible to soil detachment and transport. Differences in soil density may persist even after frost layers have thawed. This, combined with high intensity spring rains, often results in large soil losses.

Tillage and Other Soil Disturbance Effects

Soil mixing as a result of tillage alters soil structure and changes the aggregate size distribution of the soil. Soil aggregates may either be broken up as a result of the tillage operation or consolidated into larger aggregates depending on the moisture content of the soil at the time of tillage. Compaction from the tractor and tillage implement will also alter erodibility. As a result of tillage operations, the soil density is affected and, consequently, the hydrologic characteristics of the soil.

After a tillage operation, there follows a period of natural subsidence resulting from the movement of water through the soil, the weight of the soil itself, and the action of rain and wind. Subsidence is characterized by a reduction in random roughness of the soil surface due to the eroding of small peaks into valleys, compaction, redistribution of soil particles to a more dense form, and elutriation of fine material into larger voids in the soil matrix as a result of destruction of surface aggregates (Onstad et al. 1983). Differential subsidence may also occur due to areas of variable density.

In the absence of tillage operations, changes in erodibility may occur as the result of animal activity. Trampling by cattle on pasture or rangeland compacts the soil. Burrowing animals provide a source of loose material that is easily removed by raindrop impact and shallow flow. Sediment yields from undisturbed areas have been traced to this source (Yair and Rutin 1981).

Biological and Chemical Effects

Structural changes or changes in the degree of aggregation and aggregate stability also occur due to various biological and chemical processes. Growing plants affect erodibility by the physical adherence of roots and root hairs to soil aggregates and the soil stabilizing or destabilizing action of mucilage exuded by the root. Root exudates and decomposition products of crop residues stimulate different types of microbial activity, breaking down residues and producing other mucilages, which may have a strong influence in binding soil particles.

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CURRENTLY NEEDED AND AVAILABLE INFORMATION

Nearly all of the factors listed above have been studied to some extent, but few are understood sufficiently to allow their incorporation into a dynamic model predicting temporal changes in erodibility. In particular, the interactions of the various parameters have not been sufficiently examined. Their effects are interrelated to varying degrees and result in soil erodibility being a dynamic rather than a static property.

Aggregate Stability

The effect of aggregate stability on soil erodibility has been investigated in numerous past studies (Bryan 1968, Chepil 1954, Gish and Browning 1948, Low 1954, Russell and Feng 1947, Young and Mutchler 1977). However, in most cases stability has been measured by a standard slaking technique which resembles the destructive forces of flowing water. Attempts to determine soil aggregate stability under water drop impact forces have been relatively few (Bruce-Okine and Lal 1975, McCalla 1944, Pereira 1956, Smith and Cernuda 1951, Young and Onstad 1982). The stability of soil aggregates as affected by the two different types of erosive forces, surface flow and drop impact, need to be examined. This is significant from the standpoint of characterizing the two separate processes of rill and interrill erosion. A method has been developed to characterize the relative stability of soil aggregates under different erosive agents, but so far it has been used on very few soils (Young 1983). This work needs to be extended,and the effects of tillage and residue management should be included.

Freezing and Thawing Cycles or Wetting and Drying Cycles

The effect of freezing and thawing on soil erodibility has been looked at by several researchers in the past (Benoit 1973, Bisal and Nielsen 1967, Dickinson et al. 1982, Formanek et al. 1983, Leo 1963, Sillanpaa and Webber 1961, Soulides and Allison 1961). Most research has been done in Canada. Most past work in this area has been directed toward looking at the effects of freezing and thawing on water stable aggregates. This is significant, but more needs to be done on the effects of freezing and thawing on carbon dioxide release and microbiological activity, particularly nitrogen mineralization and organic matter decomposition, as they relate to soil erodibility. All of these processes are stimulated by repeated freezing and thawing cycles or wetting and drying cycles (Bristow 1983, Soulides and Allison 1961). Interrelationships of these effects could significantly influence soil aggregate stability and thus soil erodibility.

Formanek et al. (1983) have shown that soil erosion resistance is at a minimum immediately after a soil has thawed and tends to increase with time after thawing. Therefore, the greater the number of freeze-thawing cycles, the greater the time that the erosion resistance of a soil is at a minimum and the more likely soil loss is to occur. In areas such as the Pacific Northwest where winter soil temperatures hover around the freezing mark, the soil surface is apt to undergo several freeze-thaw cycles which will no doubt have a significant effect on soil erodibility. In areas of the Upper Midwest, where the winters are more extreme, temperatures are apt to dip below freezing and remain there for longer periods of time, and as a result, the soil is not apt to be exposed to as many freeze-thaw cycles. However, depending on the soil conditions at the time of initial freezing, soil aggregation and aggregate stability may still be significantly affected in the spring at the time of thawing. In more southerly climates, where the soil temperatures seldom fall below freezing, repeated cycles of wetting and drying can significantly affect soil aggregation, aggregate stability, organic matter decomposition, microbial activity, and subsequent soil erodibility.

Chemical and Microbiological Activity

A large body of evidence indicates that organic materials are important stabilizing agents in agricultural soils. The specific nature of their effect on soil erodibility, however, needs to be more closely examined. Chemical and microbiological activity in the soil varies seasonally with tillage condition, plant growth, soil temperature, and soil moisture content. About 70% of the variability in soil respiration can be accounted for by soil temperature and moisture (Bunnell et al. 1977). Different plants are known to have different effects on soil erodibility, effects which extend beyond basic differences in the amount of vegetative cover and biomass produced. These effects are likely to be chemical or biological in nature. For example, demonstrated differences in aggregate stability associated with root growth of different crops such as rye and corn have been linked to the soil stabilizing effects of root exudates and mucilages produced by microorganisms, probably principally polysaccharides, and to the possibly detrimental effects of polysaccharide decomposing bacteria (Reid and Goss 1981, Reid and Goss 1982, Tisdall and Oades 1979). Although somewhat inconclusive, the role of mycorrhizal fungi has also been linked to aggregate stability, both through their exudates as well as the entangling action of their hyphae (Sutton and Sheppard 1976). Different crops produce different exudates and stimulate different microbial populations. Quantitative differences in the amount of organic matter produced in the rhizosphere and qualitative differences in the type of organic matter produced by the roots and microorganisms result in variable effects on soil aggregate stability and subsequent soil erodibility.

Tillage and residue management can be used as a tool to manage soil microbial activity. For example, there is good reason to believe that crop residue placement will affect microbial decomposition of the residue. Tillage, rate of residue return, residue placement, and its N content all influence soil aggregation, stability, and

structure by their affects on microbial numbers and activity and the quantities of binding materials produced during decomposition (Elliott and Lynch 1984).

The stability of soil aggregates in some areas of the country is also affected by the degree to which organic materials are bound to soil surfaces by polyvalent metal ions, principally iron and aluminum (Giovannini and Sequi 1976). The root growth of different plants can influence the strength of these bonds over a growing season by the release of chelating agents in the rhizosphere which remove the metal cations (Reid et al. 1982).

Biological Activity

In some areas, principally areas undisturbed by man, biological activity can provide much of the material contributing to sediment yield from the area. This consists primarily of burrowing and digging of animals and insects, which provide a source of loose soil that is relatively easy to remove by raindrop impact and shallow overland flows. Sediment yield from undisturbed areas has been linked to annual activity of burrowing animals (Yair and Rutin 1981). The existence of human activity, however, probably overcomes any effect of such animal activity, changing the entire system.

Microtopography

It is well known that tilled soils subside and become smoother with time after tillage. This is a result of several factors acting on the surface or within the tilled layer. Among these factors are the energy transfer to the soil surface by rainfall, changing soil strength with water content as water moves through the tilled layer and changing surface conditions as raindrop energy or soil erosion redistributes the soil particles to form surface seals. Reductions in random roughness and hydraulic conductivity and increases in soil bulk density have been related to the application of water (Onstad et al. 1983). These three factors are directly related to the amount of water infiltrating into any soil surface and are particularly subject to change on freshly tilled surfaces that change rapidly during rainfall events. In general, depressional storage decreases with decreasing random roughness and increasing slope steepness (Onstad 1983). The surface area of depressions when filled is an important parameter for interception and infiltration of rainfall and increases with random roughness for low slopes. For high slopes, it increases to a maximum value at an intermediate roughness and then begins to decrease. These changes are occurring continually during the year and can significantly affect runoff and erosion from upland areas.

Interaction

The effect of any of these factors is tempered by the effects of some or all of the others. It is this interrelationship of the effects of all factors that is least understood and most in need of additional studies in order to be able to describe and predict temporal changes in soil erodibility. Once the interrelationships of the above mentioned parameters have been determined, a systematic model can be developed describing the effect on soil erodibility of temporal changes in soil characteristics resulting from weathering processes. Soil erodibility then becomes a dynamic characteristic of the soil, dependent on a number of other factors rather than a static characteristic, as it is currently treated.

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SOIL LOSS TOLERANCE

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INTRODUCTION

Responding to continued questions from a wide variety of sources on the validity and use of "Soil Loss Tolerance," the chief of the Soil Conservation Service, Peter C. Myers, in July 1983 appointed a committee to study the problem. The committee consists of SCS, national headquarters soil scientists, soil conservationists, engineers, and a geologist. I was appointed chairman. The charges were as follows:

1. Determine if the definition of T can be improved to--

    a. Clarify the relation of the concepts of sustained production and of soil regeneration.

    b. Achieve better differentiation in T values.

2. Examine desirability for adjustments in T for thick relatively uniform soils, especially loess derived soils.

3. Determine if the T concept or other means can be used to identify and define more clearly those soils vulnerable to productivity loss because of erosion.

The committee will present a final report to the chief by March 1, 1984.

Three major objectives for allowable soil loss have been set forth at various times in the past. They are: maintaining topsoil (Smith 1968), maintaining soil productivity (Wischmeier 1978), and minimizing off-site damage from erosion products (Springer 1959). The committee decided that all three objectives can and should be incorporated in a revised concept of allowable soil loss but that the three objectives need to be clearly distinguished. The team also decided to concentrate initially on allowable soil loss from water erosion and to make necessary adaptions for wind erosion at a later date.

Definitions

At this time, the committee proposes the following concepts and definitions (Fig. 1). The terms used are working terms to develop concepts and are subject to change.

Soil Loss Tolerance (T)

The soil loss tolerance is the maximum amount of erosion at which the quality of a soil as a medium for plant growth can be maintained. Maintaining the quality of a soil requires maintaining the quality of the surface soil as a seedbed for plants and maintaining the quality of the atmosphere--soil interface both to allow entry of air and water into the soil and protect the underlying soil from the forces of wind and water erosion. Maintaining soil quality also requires preserving the total soil volume as a reservoir for storing water and plant nutrients and for subsequently releasing water and nutrients for use by plants. Soil Loss Tolerance is related to erosion by water as estimated by the Universal Soil Loss Equation (USLE) and measurement of ephemeral gullies and erosion by wind as estimated by the wind erosion equation (WEQ).

Soil Delivery Tolerance (D)

The erosion limit is the maximum amount of erosion that can be tolerated for a specific conservation treatment unit (CTU) without impairing the quality of water in the watershed, the quality of air for the region, and the quality of adjacent land units whether in the same farm or not. Intended uses of water, air, and land resources and the distance to critical bodies of such resources may influence the soil delivery tolerance.

Erosion Limit (E)

The erosion limit is the maximum rate or amount of soil loss permissible as the planning objective for a conservation treatment unit.

CONSIDERATIONS IN SETTING LIMITS

The following are the major considerations for setting limits for the concepts outlined above.

Soil Loss Tolerance (T)

The maximum soil loss tolerance (fig. 2) is the amount of soil loss at which the quality of the surface soil is maintained or at which the loss of potential productivity is within socially acceptable limits. The soil loss tolerance is the smaller of these two values.

Quality of the surface soil.

This refers to the quality of the surface soil as seedbed and as the soil atmosphere interface. We believe that the quality of the surface soil is maintained if the rate of erosion does not exceed the rate at which stable organic matter can be formed. The role of organic matter formation can be modeled using information on crop residues or on rangeland, range site and condition, climate, and soil texture.

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We expect that the relatively simple guidelines for use in individual Major Land Resource Areas (MLRA's) (USDA, 1981), can be developed. Using organic matter formation as the major criterion has the advantage that a true equilibrium level can be established and no subjective decisions on what is permissible need to be made. We expect that this criterion will limit soil loss tolerance values that for deep soils, especially those on loess and other unconsolidated parent materials, are lower than the values at present.

In a few soils erosion may reduce the quality of the surface soil even if the level of organic matter is maintained. These are soils in which erosion causes subsurface soil with undesirable characteristics such as high erodibility (high k) or slow permeability to be incorporated into the surface soil. Such changes may influence the productivity of the soil as discussed in the following section.

If such changes influence future erodibility without immediately affecting productivity, we may need to establish limits on permissible increases in the soil erodibility factor (k) of the USLE.

Loss of potential productivity

Loss of potential productivity can be estimated through the use of models such as the EPIC (Williams et al. 1983) EPIC and PI (Pierce et al. 1983) PI models that are being developed by The Agricultural Research Service (ARS). The rate of loss of potential productivity in most soils is influenced by the nature and thickness of the soil (soils with a shallow root limiting layer are vulnerable) and the ease with which the substratum (C or D horizon) can be converted to subsoil. A substratum consisting of hard rock is more limiting than a substratum of loess.

This is not an equilibrium condition and a policy decision on what constitutes a permissible loss in productivity (how much? over how many years?) may need to be made at some time. After this has been done, we will be able to make the technical implementation of this decision, calculate soil loss tolerances for individual soils and make them part of the computerized SCS soil interpretation record (SOILS 5). We expect that limits based on the loss of potential productivity will result in lower soil loss tolerance primarily on relatively shallow soils and soils with a limiting soil horizon, such as a strongly developed argillic horizon (clay pan). Soil loss tolerance values based on either surface soil quality or potential productivity considerations would probably be lower than current T values for droughty soils and for shallow soils.

Soil Delivery Tolerance (D)

The soil delivery tolerance (fig. 3) is related to the sensitivity of streams, lakes, reservoirs or adjacent lands to suspended sediments and pollutants carried by sediment and to site characteristics such as the distances to bodies of water and steepness and shape of slopes. It is also related to air quality standards and societal tolerance to physical as well as aesthetic damages of dust storms. Current or planned use of land and water resources and current planning objectives for the watershed or other planning units are important considerations in setting soil delivery tolerance (D) values.

As no national standards for allowable sediment loads exist and criteria for existing delivery ratios are only now being developed, initial guidelines for Soil Delivery Tolerance may need to rely heavily on local judgment. We expect that better procedures for determining tolerances will evolve from current work on watershed modeling.

Erosion Limit (E)

The maximum Erosion Limit for a conservation treatment unit is either the Soil Loss Tolerance (T) or the Soil Delivery Tolerance (D) whichever is smaller.

IMPLEMENTATION

Concepts presented here should help SCS to rely less on arbitrary values for allowable soil loss and to arrive at critical limits that reflect better the inherent soil and watershed characteristics than the criteria SCS is using now. The SCS committee is working closely with research agencies in developing quantitative standards and operational adaptations that will allow implementation with a minimum of additional work at the State and field office level.

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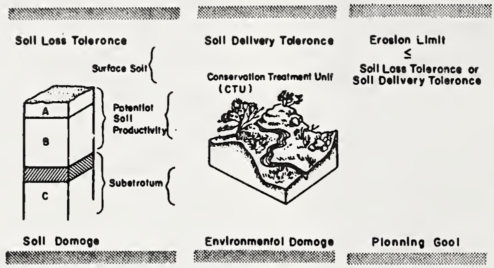

Figure 1. Soil Loss Tolerance, Soil Delivery Tolerance, and Erosion Limit.

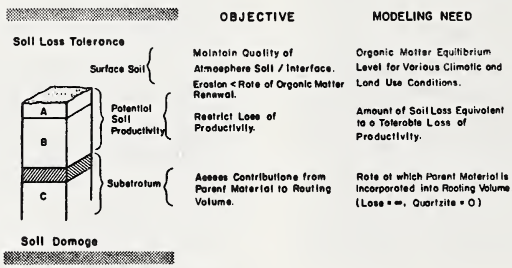

Figure 2. Objectives and Modeling Needs for Soil Loss Tolerance.

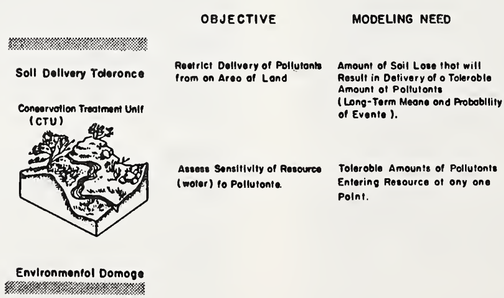

Figure 3. Objectives and Modeling Needs for Soil Delivery Tolerance.

REMOTE SENSING AND EROSION RESEARCH

Jerry C. Ritchie[1]

Remote sensing is the measurement or acquisition of information about some property of an object or phenomenon by a sensor that is not in contact with the object or phenomenon under study. A great number of sensors (cameras, radar, multispectral scanners, and so forth) and platforms (spacecraft, aircraft, truck-mounted booms, handheld camera, and so forth) can collect remotely sensed data. The questions are (1) What sensor or combination of sensors and platforms can provide useful information on erosion for the research scientist or the soil conservationist trying to minimize erosion? (2) What resolution and time intervals are needed? and (3) How can this additional information be incorporated into current procedures and models?

EXAMPLES OF THE USE OF REMOTELY SENSED DATA IN EROSION WORK

Aerial photography was first used in making soil surveys in 1927. Now every SCS conservationist uses aerial photographs to develop conservation plans. Soil surveys are routinely mapped on aerial photographs. In recent years, SCS has used Landsat Multispectral Scanner (MSS) data to improve the efficiency and speed of soil surveys and for other purposes. The Forest Service and the Bureau of Land Management (BLM) routinely use aerial photographs to assess the condition of Federal lands they manage.

Researchers have used remotely sensed data from aircraft and spacecraft along with terrain, soils, and other data in Geographic Information Systems (GIS). The GIS have been used to produce potential erosion maps for watersheds or other land units of interest. Using these systems, areas of potential erosion problems can be identified.

Aerial photographs have been used to detect and rank areas according to rill density and width in the Palouse region of the Pacific Northwest. These studies are helping to better understand the mechanism of erosion in the Palouse.

Studies in Mississippi have shown that a time sequence of aerial photographs can be used to help understand the development of stream channels and gullies. These studies are helping to better define the problems related to gully and stream bank stability.

Research in Iowa with a camera suspended from a truck-mounted boom showed that micro changes in the topography could be measured and monitored. With this information, areas of erosion and deposition within a field were measured. Such information helps to understand the difference between the amount of erosion estimated in the field and the amount actually measured at the edge of the field.

In Georgia controlled platform-mounted photographic sequences have been used to accurately measure very small changes in gullies, channels, and even rills. Such photographs have provided information on the basic processes involved in gully and channel formation and expansion.

Remote sensing has been used in many applications to determine land cover. One unique example is research in the Southwest where the area covered by the desert pavement was measured. The desert pavement can effectively dissipate rainfall energy. Information on ground cover helps understanding erosion processes under many conditions.

Remote sensing has been used to estimate near-surface-suspended sediments in water. Since a lake is an effective integrator of the sediment produced on its watershed, information on suspended sediments can be used to identify watersheds with potential problem areas of erosion.

These are just a few examples of how remote sensing techniques have been used to study erosion. Numerous other examples could be cited and discussed.

RESEARCH ROLE FOR REMOTE SENSING IN EROSION

High speed photography has been used to study raindrop impact, and others have used this tool to improve measurements of erosion processes. Various remote sensing tools can collect information on sequences of events from which quantitative information about the processes can be developed. Time-lapse photographs or sequences of photographs of raindrop impact, rill and channel development, and movement and deposition of particles within a field are examples where remote sensing technology can provide better information than can be collected by other methods. Likewise, turbidity in water bodies can be continuously monitored. Research is needed to develop better interpretation methods and to combine the information from available sensors and resolutions to better understand the processes involved.

While remote sensing technology is a valuable tool for studying basic processes of the erosion cycle, the most valuable use of remotely sensed data may be to better understand and measure landscape properties.

There are numerous precise quantitative methods for measuring and describing the properties of a point in the landscape (watershed). However, watershed engineering and soil science quickly become more of an art than a science when the engineer or the soil scientist puts spatial interpretations on these point measurements.

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Accurately mapping the spatial properties of a landscape is a major challenge for all natural resource management projects. Properties of the landscape, like point samples, exhibit structure, function, and change. There are few concepts or theories on how to analyze landscape-based information. Various remote sensors measure spatially distributed properties of a landscape. Once spatial information is available on a watershed, the challenge is to use it effectively. Current theory, models, and systems are based on point samples. Systems must be developed to effectively integrate spatial, temporal, and point source data for a watershed.

Depending on resolution, remote observations can provide spatial integration or point measurements of watershed properties. Repetitive measurements provide temporal data. Methods are needed to better quantify the spatial and temporal properties of the landscape from the remotely sensed data. Concurrent research is needed on the application of spatial and temporal data in any natural resource model. Without appropriate models and systems, spatial and temporal data can not be used effectively.

Remote sensing is not a panacea. Many watershed properties, such as particle size of the B horizon, cannot be measured by remote sensing. Research at the Hydrology Laboratory has shown that microwave technology can provide estimates of the spatial distribution of moisture in the soil across the landscape. More research is needed to quantify the estimates and use them in resource models.

Preliminary research has shown that the spectral properties of soils can probably be related to the productivity of the soil. As the A horizon is eroded away, the spectral properties of the soil changes. Research is needed to determine if these spectral properties can be used to map productivity across the landscape.

Remote sensing can provide spatial and temporal information on properties related to erosion, hydrology and productivity. Research is needed to quantify these remotely sensed data. Improved data quality is essential if remotely sensed data are to be used in an operational mode.

While better quality spatial data are needed, research on systems or models that can use such data is also needed. Current models are limited in their ability to handle such data.

Geographic Information Systems or geo-data bases currently have the capability to handle spatial data and to overlay numerous spatial properties and produce maps based on combinations of information in the GIS. As noted before, GIS have been used to produce erosion maps of watersheds based on the USLE. Research is needed to determine how to most effectively use GIS in connection with natural resource models. Can the spatial information in a GIS or similar system be used effectively with current natural resource models?

SUMMARY

Current remote sensing technology can measure many spatially distributed properties easily and inexpensively. Existing models use mostly point measurements; hence, models or systems that use spatial data need to be developed. Existing models may have to be modified extensively to use such data. The converse approach would be to research how spatial data could be lumped or integrated into a few descriptors. These few descriptors could represent the spatial nature of landscapes and thus simplify the data input to distributed models. Extensive research is needed to develop procedures that effectively use spatial, temporal, and GIS data, when available, and to interpret them meaningfully through natural resources models.

EROSION ASSESSMENT - CONCERNS OF THE SOIL CONSERVATION SERVICE

Gerald M. Darby[1]

The Soil Conservation Service (SCS) needs to assess soil erosion for two main purposes. One is to help farmers and other land users plan and apply a conservation system for the land. The other purpose is to inventory our soil and water resources. These resource inventories help government agencies at the national, state, and local level develop and evaluate conservation policies and programs. For example, national assessments of soil erosion help SCS and the Agricultural Stabilization and Conservation Service (ASCS) designate target areas of high erosion for technical assistance and cost sharing.

SCS made its first national inventory of soil and water conservation needs in the mid-1950's; there was a second one about 10 years later. Neither of these assessed the amount of soil erosion. They inventoried soils from the standpoint of land use, inherent susceptibility to erosion, and conservation treatment needs. The natural resources inventories that SCS conducted in 1977 and in 1982 included estimates of sheet and rill erosion in all 50 states and the Caribbean area and of wind erosion in the 10 Great Plains States. The Universal Soil Loss Equation (USLE) and the Wind Erosion Equation (WEQ) developed by ARS made these erosion assessments possible. Not assessed was concentrated-flow erosion, also called ephemeral gully erosion. SCS did not assess this type of erosion primarily because convenient assessment tools were not available.

Models that help estimate concentrated-flow erosion before and after land treatment are badly needed by the SCS and ASCS. For example, ASCS's pilot program of variable ratio cost sharing requires a complete estimate of soil erosion in each treatment area. Under this program, the ASCS share of the cost of conservation measures varies with the amount of erosion the farmer prevents. Changes in sheet and rill and wind erosion due to treatment can be estimated by using USLE and WEQ. Erosion reduction in large gullies is fairly easy to estimate by calculating the annual rate of gully erosion prior to treatment and assuming that any reduction in the rate after treatment is the result of the treatment. Estimating erosion from concentrated flow that produces ephemeral gullies is difficult and time consuming. One has to use cross sections to determine the normal ground elevation before erosion, calculate the volume of the voided area, and determine the number of years involved in the erosion, then determine the annual rate of erosion. This still leaves the problem of estimating the reduction in ephemeral gully erosion provided by the planned treatment.

SCS needs models for assessing and predicting erosion on roadsides, streambanks, and construction sites. Also of concern is assessing the impact of soil erosion in terms of offsite damages and long-term productivity of soils. Another need is a quick-response system to detect and report erosion with minimum use of SCS field people. Ongoing work to more effectively measure wind erosion and land damage due to wind erosion needs to be fully supported. Greater use of remote sensing and other automated methods for detecting and reporting soil erosion and sediment problems is needed. This includes the development of a quick-response mechanism for reporting erosion, similar to that used in SCS's snow survey and water supply forecasting system.

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SYSTEMATIC PREDICTION OF WIND EROSION: PHASE 1

George W. Cole[1]

INTRODUCTION

Systematic prediction of soil loss due to wind erosion has been shown to involve the time and space integration of the normal component of the surface soil loss vector (Cole 1984). The general spacial integration techniques that were developed in that paper are applied here for a circular field. This field shape was chosen to demonstrate the technique because the mathematics and resulting equations are relatively simple. Application to complex field shapes requires numerical integration and data entry techniques which are unique to digital computers. The development of this machine solution capability will represent phase 2.

METHOD

The general mass-flow-rate equation developed for any convex-shaped field is given (Cole 1984) as

$$\dot{m} = - \oint_C q\{r[R(u(s,\beta)), u(s,\beta)], h,J\} \cdot \{\frac{dy}{ds} \cos \beta - \frac{dx}{ds} \sin \beta\} \, ds \qquad (1)$$

(see the list at the end of the summary section and figures 1 and 2 for symbol definitions).

In order to use this equation, we must define the boundary of the field in terms of s, the distance along the perimeter. Furthermore, the soil loss line intensity function q (see fig. 1), which is assumed available from wind tunnel studies, is a function of r, the distance from a nonerodible boundary. From equation 1 and figure 2 it can be seen that ultimately q, via a series of axis transformations, becomes a function of s, and β the wind angle. Figure 2 illustrates the relationship between the wind oriented coordinates R,u and the fixed coordinates x,y by which the field shape, C, is described.

To simplify equation 1 requires a mathematical description of the compound function of r, that is,

$$r[R(u(s,\beta)), u(s,\beta)] \qquad (2)$$

and

$$\frac{dy}{ds} \cos \beta - \frac{dx}{ds} \sin \beta \qquad (3)$$

where x(s) and y(s) are a parametric description of the field boundary and the h,J have been suppressed for simplicity in equation 2 since they do not affect the derivation. For this particular field shape, it is expedient to convert the s distance to ω via the following definition of an arc:

$$\omega = s/a. \qquad (4)$$

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We shall first develop equation 2 by starting with the following equation (which is derivable from fig. 1) relating r to R:

$$r = R - R_1(u) + \Psi(R_1(u),u). \qquad (5)$$

Equation 5 represents the shifting of the r axis along the R axis due to two causes. The R_1 term is the shift due to the field boundary at the inflow side and Ψ the shift due to the magnitude of the soil inflow. Both of the effects are independent; that is, even if the inflow were zero (that is, $\Psi = 0$), the value of q(r) would vary due to the position of the field boundary $R_1(u)$. A more detailed explanation of equation 5 is developed in Cole (1984).

We are interested in constraining R to the boundary of our field, since this is where the inflow and outflow exist. We note from figure 2 that R as a function of u is multivalued and, as such, it is not useful for integration until it is made single valued. We do this by subdividing the perimeter of the circle into two functions depending on ω:

$$R = \begin{cases} R_2(u) & 0<\omega\leq\pi \\ R_1(u) & \pi<\omega\leq 2\pi. \end{cases} \qquad (6)$$

Substitution of equation 6 into 5 yields

$$r = \begin{cases} R_2(u) - R_1(u) + \Psi(R_1(u),u) & 0<\omega\leq\pi \\ R_1(u) - R_1(u) + \Psi(R_1(u),u) & \pi<\omega\leq 2\pi \end{cases} \qquad (7)$$

We see that to evaluate equation 7 requires the description of $(R_2 - R_1)$ and R_1, since Ψ, the inverse of q(r), is known.

From figure 2 it can be seen that $(R_2 - R_1)$ is any chord that intersects the circle and is parallel to the R axis. From trigonometry we have

$$R_2 - R_1 = 2a \sin \omega(s). \qquad (8)$$

In order to determine R_1, the second unknown in equation 7, we will utilize one of the coordinate transformation equations between the x,y and R,u coordinate systems,

$$R = x \cos \beta + y \sin \beta. \qquad (9)$$

To determine R_1 we must constrain equation 9 to the perimeter of the circle by causing the x,y coordinates to be the set of coordinates describing the circle in terms of s, that is,

$$R = x(s) \cos \beta + y(s) \sin \beta. \qquad (10)$$

The analytic expression for x(s) and y(s) can be determined from figure 2 by application of trigonometry as

$$x(s) = j + a \sin (\omega + \beta),$$

$$y(s) = k - a \cos (\omega + \beta). \qquad (11)$$

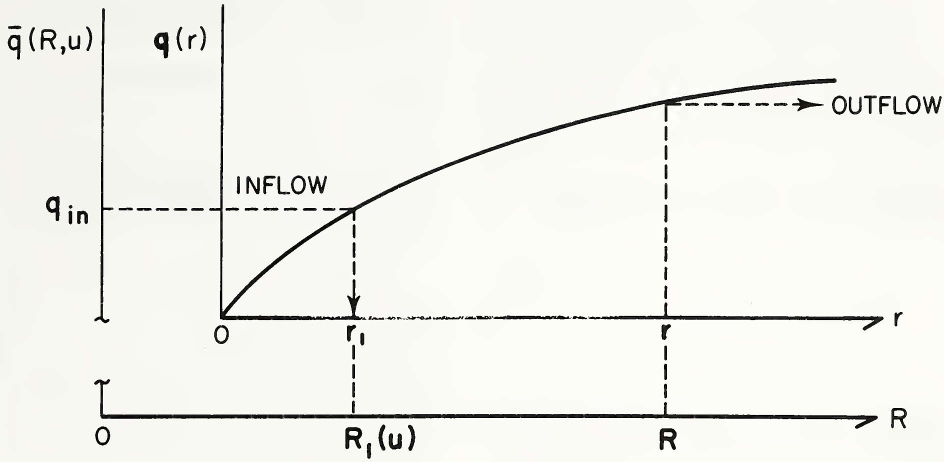

Figure 1.--Soil loss line intensity function q, relative to two axes, r and R.

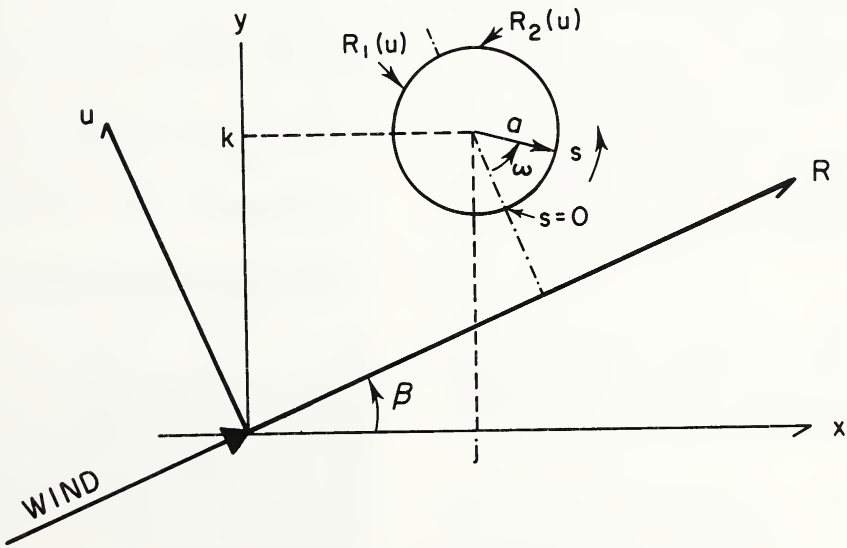

Figure 2.--Field shape, functions, and coordinate systems.

Substitution of equation 11 into 10 yields

$$R = j \cos \beta + k \sin \beta + a \sin \omega(s). \tag{12}$$

Now equation 12 does not yet describe R_1. This is accomplished by forcing R, which describes the total perimeter, to describe only the R_1 portion, that is,

$$R_1 = j \cos \beta + k \sin \beta - a|\sin \omega(s)|. \tag{13}$$

Now substitution of equations 8 and 13 into 7 yields the following equivalent of equation 2:

$$r = \delta\, 2a \sin \omega + \Psi(j \cos \beta + k \sin \beta - a|\sin \omega|) \tag{14}$$

$$\text{where } \delta = \begin{cases} 1 & 0<\omega\leq\pi, \text{ outflow} \\ 0 & \pi<\omega\leq 2\pi, \text{ inflow.} \end{cases}$$

To complete the evaluation of the components of equation 1, we must evaluate equation 3. This is done by first evaluating the derivatives of x(s) and y(s) (utilizing equation 11) and substituting the derivatives into equation 3. The results are

$$\frac{dy}{ds} \cos \beta - \frac{dx}{ds} \sin \beta = \sin \omega(s). \tag{15}$$

Substituting equations 14 and 15 into equation 1 and using equation 4 to determine $d\omega$ in terms of s results in the following mass-flow-rate equation for a circular field:

$$\dot{m} = \int_0^{2\pi} q(\delta\, 2a \sin \omega + \Psi(j \cos \beta + k \sin \beta - a|\sin \omega|),\ h,J)\ a \sin \omega\ d\omega \tag{16}$$

where δ is defined in equation 14.

Now equation 16 can be further simplified if we assume a zero soil inflow condition (that is, assume that the boundary of the field is nonerodible), then

$$\dot{m} = \int_0^{\pi} q(2a \sin \omega,\ h,J)\ a \sin \omega\ d\omega. \tag{17}$$

EXAMPLE

To demonstrate the utility of equation 17, we shall calculate $\dot{m}$ for a typical center pivot irrigation system using published q curve data (Chepil 1957, Fig. 1, curve d). To simplify the integration, we represent this curve as

$$q = \begin{cases} \alpha r & r < r_0 \\ \alpha r_0 & r \geq r_0 \end{cases} \tag{18}$$

where r_0 is the breakpoint of this piecewise linear representation and α is the slope which is assumed constant.

Substitution of equation 18 into 17 results in two integrals. These two integrals result in this case because the numerical values r_0 and a are such that

$$0 < r_0 < 2a. \tag{19}$$

This results in two regions for ω, which are separated by ω_0, where

$$\omega_0 = \sin^{-1}(r_0/2a). \tag{20}$$

Since the soil loss rate is equal for each half of the circle, we integrate over one-half the circle and double the results, that is,

$$\dot{m} = 2\left(\int_0^{\omega_0} \alpha r\ a \sin \omega\ d\omega + \int_{\omega_0}^{\pi/2} \alpha\ r_0\ a \sin \omega\ d\omega\right) \tag{21}$$

where

$$r = 2a \sin \omega \qquad 0<\omega\leq\omega_0. \tag{22}$$

Integration of equation 21 results in

$$\dot{m} = 2\alpha(a^2\omega_0 + \cos \omega_0(ar_0 - a^2 \sin \omega_0)). \tag{23}$$

The numerical values from Chepil's curve (Chepil 1957) expressed in SI units are

$$\alpha = 7.158 \times 10^{-4}\ t/(m^2 \cdot h)$$

and

$$r_0 = 502.9 \text{ m}.$$

For a typical center pivot irrigation field on a 1/4 section,

$$a = 402.5 \text{ m}.$$

From equation 20 we find that

$$\omega_0 = 0.675 \text{ radians}.$$

Finally, substitution of these four values into equation 23 yields

$$\dot{m} \simeq 270\ t/h$$

as the rate of soil erosion.

SUMMARY

A method for incorporating a specific field shape into the general mass-flow-rate equation has been demonstrated. The resulting equation (equation 16) allows for the use of a single line intensity function, which has been shifted and transformed appropriately. The equation considers not only the surface conditions implied by J but also the wind angle, radius of the circle, the offset distances j and k, and the magnitude of the soil inflow.

We note that if there is no inflow--that is, if the field boundary is nonerodible--then the mass flow rate is independnet of the wind angle.

This method, while practical for simple geometric shapes, becomes quite impractical for nonanalytical shapes, and the numerical integration of equation 1 must be performed.

Symbol	Definition and dimensions[2]
a	radius of circle, L
C	the perimeter of the field surface, L
h	distance from soil surface to top of the field control volume. This also may be considered the saltation height, L.
j	x coordinate of the center of the circle, L
J	the set of surface conditions which affect q
k	y coordinate of the center of the circle, L
$\dot{m}$	the soil mass-flow rate through a specified surface, $M\ T^{-1}$
q	line intensity, the soil flow rate per unit width, $M\ L^{-1}T^{-1}$
$\bar{q}$	same as q but with respect to the R,z axis, $M\ L^{-1}T^{-1}$
r	distance along the r axis, L
r_0	breakpoint of q in equation 18, L
R	distance along the R axis, L
s	arc length of perimeter C, L
u	distance along the u axis, L
x	distance along the x axis, L
y	distance along the y axis, L
α	slope of linear part of q in equation 18, $ML^{-2}T^{-1}$
β	wind angle, the angle of the wind relative to the positive x axis, counterclockwise positive (see fig. 2), dimensionless
δ	defined in equation 14, dimensionless
π	3.14159..., dimensionless
Ψ	the inverse function of q(r)
ω	see equation 4, dimensionless
ω_0	see equation 20, dimensionless

Subscripts

i	index, 1, 2, 3 ... various surfaces and/or arc lengths

[2] M, L, and T as dimensions refer to mass, length, and time.

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FACTORS AFFECTING FURROW EROSION

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D. L. Carter, and R. C. Rosenau*

FACTORS AFFECTING SHEAR FORCE

Erosion occurs when the shear force exerted by water on a soil unit exceeds the forces binding that unit to underlying soil. The primary factor affecting shear force exerted by water on the soil is velocity of the water. Velocity is determined by amount of water flowing per unit time and by slope of the furrow. Relative effects of slope and furrow flow rate on average water velocity can be deduced from equation 1, which is Manning's equation for flow in open channels, where Q is flow rate (M^3/s), A is cross sectional area of flow (M^2), S is slope (M/M), P is wetted perimeter (M), and n is the coefficient of roughness.

$$Q = A^{5/3} S^{1/2}/(n P^{2/3}) \qquad (1)$$

For many furrow shapes (that is, V-shaped), when water supply rate or slope varies, the breadth (B) of the water-filled cross section retains essentially the same ratio to its depth (D), that is B/D= K. When this ratio remains constant, B= KD, $A= K'D^2$ and $P= K''A^{1/2}$. Substituting the latter relation in eqation 1, and solving explicitly for A gives

$$A = (Qn/K''' S^{1/2})^{3/4}. \qquad (2)$$

Substituting this value of A into the definition, v=Q/A of the average stream velocity, and recognizing that bed shear stress, T, is proportional to v^2 gives

$$T = (K_o/n^{3/2}) \; S^{3/4} \; Q^{1/2}. \qquad (3)$$

Calculation of shear force on the bottom of an infinitely wide channel gives equal exponents for Q and S. Less sensitivity of T to Q than to S in furrows where B/D is constant (equation 3) is due to wetted perimeter increasing when Q increases, which spreads the restraining force over a larger area.

Amount of erosion will be determined by amount of particles or aggregates on the furrow perimeter which do not cohere strongly enough to the underlying soil to withstand shear stress. The specific nature of the relationship between erosion and the shear stress will be determined by the soil properties, but the exponent of the slope term (S) should be 1.5 times the exponent of the flow rate term (Q) if B/D remains constant as flow rates and slope vary and furrows erode. This constancy is difficult to predict or quantify. However, several data sets are available in which effects of slope and flow rate on erosion are related. The ratios of the slope and flow rate exponents found to fit the data sets best to equations of the type $E= kS^aQ^b$ are compared in table 1.

Table 1.--Comparison of the ratios of a/b in the equation, $E=Ks^aQ^b$ relating erosion (E) to slope (S) and flow rate (Q).

Investigators	a	b	a/b	Location
*Carter et al	2.7	1.8	1.5	ID Farms
Evans & Jensen (1952)	2.3	1.5	1.5	ND
Gardner & Lauritzen(1946)	1.5	1.0	1.6	Flume
Israelson et al(1946)	1.8	1.0	1.2	UT Farm
Israelson et al(1946)	1.6	1.2	1.2	UT Farm
Israelson et al(1946)	1.4	1.0	1.4	UT Flume
*Trout, Brown, & Rosenau	2.1	1.4	1.5	ID Farm

*Unpublished data

Only two of the a/b differed more than 0.1 from 1.5. Pictures in the Israelson et al. publication indicate that their furrows with a/b values of 1.2 and 1.3 had particularly broad flat bottoms. Many furrows in the studies where a/b was 1.5 ± 0.1 also developed relatively flat bottoms, but the assumption of B/D being constant was apparently close enough to reality for a/b to be practically 1.5. The consistency of the a/b= 1.5 relation is sufficiently good to suggest its use to decrease the data taking needed to adequately characterize erodibility of soils. The data sets generally indicate that the erosion, E, is a power function of the shear stress shown in equation 3, that is,

$$E=T^m=(K_o/n^{3/2})^m \, (S^{3/4} \, Q^{1/2})^m$$
$$=kS^aQ^b \qquad (4)$$

where m= 4a/3 or 2b. Data sets needed to estimate m and $(K_o/n^{3/2})$ are measures of runoff and sediment yield (1) on a known slope at two flow rates or (2) at a known flow rate on two slopes. Data collected by Carter et al. indicate that the pertinent slope is that which is immediately upstream from the sediment measuring station.

High slopes and flow rates often cause rapid erosion of cultivated soil which slows down or stops at cohesive plow pans or other layers in which cohesion withstands the shear. In analyses of the Trout et al. and Carter et al. data, measurements were not used to help determine the exponents if erosion had already proceeded down to an obviously more cohesive underlying soil.

While the ratios of a/b for the soils in table 1 are reasonably consistent, associated values of m and $K_o/n^{3/2}$ varied greatly even within soil series. Factors which account for substantial portions of these variations are discussed in the following sections.

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IRRIGATION HISTORY, ROOT FABRIC AND TIME SINCE TILLAGE

The bottom curve in figure 1 shows erosion from Portneuf silt loam as a function of rate of runoff during the second irrigation following initial cultivation and furrow forming. The field was cultivated again on July 26, 1983. During the following irrigation on August 1, 1983, erosion from these furrows increased substantially, particularly at the high rate of flow. The lesser increase at lower flow rates was probably due to increased roughness of the furrow, caused by the cultivation, which slowed the water and increased the wetted perimeter. At higher flow rates channels were quickly smoothed by more rapidly flowing water and more complete disintegration of quickly wetted clods. During successive irrigations the exponent associated with flow rate decreases because easily eroded soil has been removed. Part of the decreased erosion in the soil following winter wheat (fig. 2) appeared to be due to the furrow bottom encountering soil consolidated by root fabric. Curves in figure 2 are averages for four irrigations of a bean crop. Straw in furrows also decreases erosion (Aarstad and Miller 1980) substantially. However, little straw was left in these furrows following harvesting of the wheat for silage. Mech (1959) provides some of the most comprehensive data and astute observations on factors affecting furrow erosion.

Another factor causing decreased erosion in the non-tilled soil in figure 2 is the tendency of this soil to become more cohesive with time. Increases of wet sieve aggregate stability with time are shown for moist and air-dried Portneuf soil in the two left curves in figure 3. Bonds in this soil were broken by shear when moist. Some aggregates were then air dried and others kept moist for the indicated times. Some dried aggregates were then brought back to moisture levels of $\theta = 0.13$ and 0.31 by passing moist air from a vaporizer through them. Bonds reformed rapidly in aggregates with high water contents. In air-dried soil (about one molecular layer of water on mineral surfaces) formation of these bonds took 100 to 400 times as long. These differences in rates are of the same order as differences in diffusion rates measured (for example, VanSchaik and Kemper 1966) in soils at these water contents, indicating that diffusion of ions and molecules through the liquid phase to particle-to-particle contacts where they bond the particles together may be the rate controlling mechanism.

Since cultivation is effective in the disruption of such bonds, it is probable that cultivation and lack of time to regain cohesion plays a major role in higher erosion of tilled soils (that is, fig. 2).

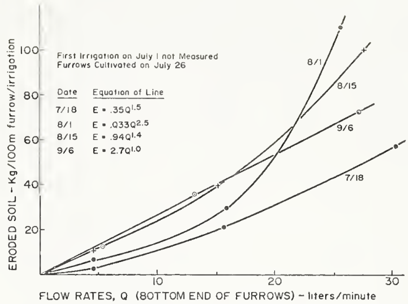

Figure 1. Effects of flow rate and sequence on erosion of Portneuf silt loam on 1 percent slope following fallow.

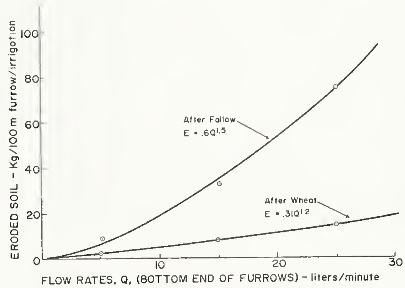

Figure 2. Effects of winter wheat and flow rate on furrow erosion during the following summer.

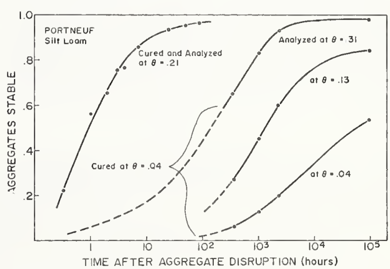

Figure 3. Increases in aggregate stability with time of moist and air dry soil.

INITIAL WATER CONTENTS AND WETTING RATES

During 1982, runoff and erosion were measured from furrows in a bean field on Portneuf silt loam during six successive irrigations. Sediment content of water during the third and fourth irrigations was much lower than in the other irrigations (fig. 4). The only apparent physical differences recorded were traces of precipitation prior to irrigation. These traces of precipitation, followed by clear nights and heavy dew, increase water content of the immediate soil surface from 1 or 2 percent up to 5 to 10 percent.

Differences in wet sieve aggregate stability of 1- to 2-mm aggregates of Portneuf silt loam at different initial water contents are indicated by intersections of the curves in figure 5 with the ordinate. Aggregates with these initial water contents were also wetted to saturation at different rates by placing them on filter paper and applying water at different rates to the filter paper. For portions of the furrow wetted quickly by direct contact with flowing water, increasing initial water content from 2.7 to 9.0 percent would increase aggregate stability from about 16 percent up to 58 percent. For aggregates on portions of the furrow where wetting by capillary action took about 60 seconds, increase in stability would be from about 52 up to 73 percent. These data substantiate the possibility that the reductions in sediment load of the runoff during the third and fourth irrigations (fig. 4) resulted from increases in initial soil water content which increased stability of aggregates in the wetted perimeter of the furrow. When aggregates were wet slowly, taking 30 minutes or more to go from dry to wet (fig. 5), they were all highly stable.

To determine whether rapid wetting increases erosion, two pairs of furrows each 100 meters long, were irrigated with identical amounts of water. One of each pair had an initial supply rate of 38 L/min for 1 houe, which was then dropped to 80, 60, 40, and 20 percent of this rate in successive hours. The other furrow of each pair was provided with 20 percent of 38 L/min for the first hour and this rate was raised by 40, 60, 80, and 100 percent in successive hours. Erosion during these 5 hours of irrigation for these quick and slow wetted furrows is shown for the first irrigation following cultivation in figure 6. Faster wetting more than doubled erosion during the irrigation following cultivation. The faster wetting rate reduced water intake by 32, 17, and 19 percent on the first, second, and third irrigations following cultivation.

Analysis of the data indicate that the increased erosion was caused by both increased runoff and decreased cohesion.

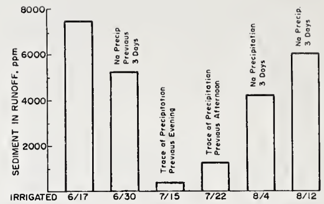

Figure 4. Differences in sediment concentration of furrow runoff.

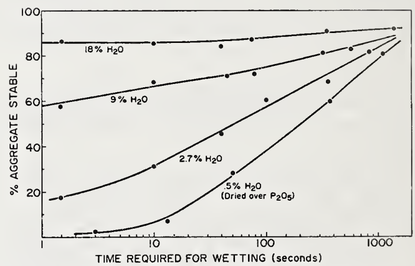

Figure 5. Aggregate stability as a function of initial water content and rate of wetting prior to immersion (Portneuf soil).

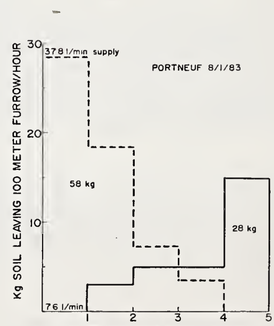

Figure 6. Effect of wetting rate on furrow erosion (Portneuf, August 1, 1983).

CONCLUSIONS

Furrow erosion is a function of the shear stress, which is an exponential function of furrow slope and flow rate. The exponent of slope is generally about 1.5 times the exponent of flow rate. Soil cohesion and fabric of roots and other organic residues in the soil provide resistance to erosion. Cohesion of soils is a function of type of, and time since, preceding tillage, water content prior to wetting, and rate of wetting at the inception of the irrigation. Faster wetting causes more erosion.

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EROSION AND SEDIMENT YIELD RESULTING FROM FURROW IRRIGATION

Neville M. Curtis, Jr.[1]

The Soil Conservation Service (SCS) currently is studying how to predict sediment yield resulting from irrigation. Sediment accumulating at the end of a furrow increases maintenance and cost of farming operations and reduces water quality downstream.

Physical damage to the irrigated field can be measured by determining where and how much soil is detached or scoured in the furrow and where and how much of that detached material is deposited. In 1983, SCS personnel in Colorado, Oregon, and Washington received target money to measure erosion due to furrow irrigation. Using a procedure developed at the West National Technical Center, they measured the area of many furrow cross sections before and after each irrigation, for different crops, soils, and slope gradients.

Preliminary analysis of some of that data indicates that under certain conditions, erosion in the furrow may be three to four times as great as the sediment yield of the field. Consequently, when looking only at the volume of sediment leaving the field we are many times not seeing the full erosion picture.

SCS expects to finish analyzing these data in 1984. We hope to be able to predict erosion in the field and to better understand what happens as a result of this erosion. With a comprehensive understanding of the various factors involved in furrow erosion, we should be able to develop practices to reduce the erosion.

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STRUCTURAL MEASURES TO CONTROL EROSION

Walter K. Twitty[1]

Conservation tillage is a highly effective single conservation practice to control erosion, but an unacceptable amount of sheet and rill, concentrated-flow, and gully erosion takes place in many fields where conservation tillage is used.

Conservation tillage, along with other conservation practices, should be a part of a resource management system. The combination of practices in the system must be suited to the kind of soil and land form, particularly degree and length of slope. Water disposal systems are essential on most fields. The use of structural practices to control erosion increased in many states in 1983.

This paper shows how structural practices fit into a modern resource management system for controlling sheet,rill, gully, and concentrated-flow erosion. The paper also points out that structural practices need to be considered in models dealing with cropland erosion.

TERRACES

Terraces are one of the oldest and most common types of conservation practices used for erosion control. They perform a function that no other practice does. They intercept runoff water before it becomes erosive, and they conduct the water, at a nonerosive velocity, to a stable outlet.

Terraces designed by SCS control the peak runoff from a 10-year frequency, 24-hour-duration storm. The Soil Conservation Service terrace standard has two recommended procedures for determining terrace spacing. One uses the Universal Soil Loss Equation. This method results in a spacing based on the tolerance level for the particular soil, the local climate, the steepness and length of slope, and tillage practices. The other method is the horizontal interval method that considers slope, climate, cropping management practices, and soil erodibility. Neither method considers erosion by concentrated flow. However, the CREAMS model addresses concentrated-flow erosion and could be useful in determining terrace spacing where concentrated-flow erosion is the major problem to be solved by terracing.

Terraces require outlets. Infiltration, vegetative, and underground outlets are the three types commonly used, alone or in combination. In some cases, grade-stabilization structures are used in the water-removal system. Subsurface drains may also be used as a companion practice to control extreme wetness.

Terraces are usually parallel, and the spacing is fitted to the machinery and farming methods. Constructing parallel terraces requires departure from the contour for short distances in some areas and crossing some natural watercourses. In so doing, temporary storage basins are created. Grassed waterways are not always practical for releasing water from the basins.

Underground outlets, usually corrugated drain tubing, can be used to remove the water. Surface runoff is temporarily stored in the small basins, and flood storage may be used to reduce the size of conduit needed. This reduces the peak rate as well as the cost of the structure. Most basins are designed to store the runoff from a 10-year, 24-hour-duration storm and release the runoff in 24 hours. In the areas where rainfall is higher, a flood-routing procedure is used to reduce the storage required and the height of the terrace ridge. Terraces do not solve every problem nor do they function alone.

Terraces are only a part of a resource management system, and they must be planned, installed, and used that way if they are to function satisfactorily.

WATER AND SEDIMENT CONTROL BASINS

On irregular topography where terracing is not practical, water- and sediment-control basins are becoming popular.

Water- and sediment-control basins are earth embankments or a combination ridge and channel generally constructed across the land slope or minor watercourses to form a sediment trap and water-detention basin. They usually have an underground outlet. The basins reduce concentrated-flow and gully erosion.

Water- and sediment-control basins alone are not intended to control sheet and rill erosion. In combination with terraces, contouring, conservation cropping systems, conservation tillage, and crop residue management, these basins can be part of a resource management system to protect soil and water resources. Most basins are spaced about the same as terraces, using the horizontal-interval method to determine the spacing. Here again, CREAMS could be helpful in determining basin spacing because it addresses concentrated-flow erosion.

DIVERSIONS

A diversion is a channel and ridge constructed across the slope. Diversions reduce erosion by diverting runoff from higher-lying areas. Such runoff damages cropland, pastureland, or other conservation practices, such as terraces or stripcropping. Diversions also divert water from concentrated-flow areas, active gullies, or critical sediment-source areas.

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Outlets for diversions are usually either vegetative or underground. Grade-stabilization structures such as pipe drops, toe wall drop structures, box inlet drop structures, and rock- or concrete-lined chutes are also outlets for diversions.

GRASSED WATERWAYS

Grassed waterways are outlets for other structural practices. In combination with other practices, they reduce erosion resulting from concentrated runoff.

RESOURCE MANAGEMENT SYSTEMS

Effective erosion control requires a mix of management, vegetative, and structural practices coordinated into a complete soil and water conservation system. For example, contour farming loses its effectiveness as the slope length increases unless some structural practice collects and removes surface runoff. Conservation tillage also needs the support of structural practices as water concentrates and slopes increase in steepness or length. Planners should always keep in mind that one practice will not solve all resource problems.

SEASONALLY EPHEMERAL CROPLAND GULLY EROSION

G. R. Foster, L. J. Lane, and W. F. Mildner[1]

WHAT IS AN EPHEMERAL CROPLAND GULLY?

Is it the same as an eroded concentrated flow channel? -- The topography of most fields causes overland flow to converge into a few major natural waterways (concentrated flow areas) before leaving the fields. These concentrated flow areas are tilled, leaving the soil highly susceptible to erosion. Most erosion in these channels is from storms soon after seedbed preparation (hence seasonal). After tillage, many soils reconsolidate, and these channels become much less erodible over time during the growing season. These eroded channels are much wider than rills (hence gullies), but unlike the traditional definition of a gully being an eroded channel too large to cross and obliterate with tillage equipment, concentrated flow areas are tilled annually on cropland and partially or completely filled in (hence emphemeral, transient, short lived). Flow in these channels is flashy and only occurs during and shortly after rain events (hence ephemeral flow).

Rills tend to be numerous, parallel, and narrow, while concentrated flow channels tend to be few and wide. Whereas the position of rills varies from year to year, concentrated flow erosion generally occurs in the same location each year. Concentrated flow areas slowly become incised over several years, steepening adjacent overland flow slopes and accelerating nearby sheet and rill erosion. In plan view, concentrated flow channels are usually dendritic, but sometimes tillage marks influence their pattern. The channels may be parallel where heavily influenced by tillage marks and may be difficult to distinguish from large rills.

On soils susceptible to erosion when tilled, concentrated flow erodes through the tilled surface soil. After reaching more resistant, untilled soil, downward erosion slows, the channels widen, and erosion decreases. On soils uniformly erodible with depth, eroded concentrated flow channels are narrower, deeper, and more incised than when the untilled soil beneath the tilled zone acts as a nonerodible layer. Definitions and characteristics of sheet and rill erosion, ephemeral cropland gully erosion, and gully erosion are given in table 1.

EXTENT OF EPHEMERAL CROPLAND GULLY EROSION

When ephemeral gully erosion is severe, grassed waterways or terrace systems are installed to essentially eliminate it. Historically the issue of erosion by concentrated flow has been one of whether or not the channel is stable. In general, it was not a matter of estimating erosion under present conditions and estimating the reduction in erosion from control of concentrated flow erosion with installation of conservation practices. Since 1980, a need of quantitative estimates for this type of erosion has developed, prompting the USDA Soil Conservation Service (SCS) to initiate a field survey program in several States, including Alabama Georgia, Maine, and Washington, to measure field erosion by concentrated flow. Preliminary results suggest that erosion by concentrated flow in some fields may be as great as sheet and rill erosion.

Ultimately, SCS needs a model to estimate this erosion for its assessment and planning programs and has contracted with USDA Agricultural Research Service (ARS) and others to collect field data needed to develop and validate a model and to develop and improve models for estimating erosion by concentrated flow. Organizations involved in this research include ARS locations at Oxford, MS; Ames, IA; and Watkinsville, GA; U.S. Army Corps of Engineers at Vicksburg, MS; Colorado State University; and University of Georgia. Additionally, rill and furrow erosion research at the ARS locations of Pullman, WA; Kimberly, ID; Columbia, MO; Lincoln, NE; and W. Lafayette, IN is also providing information.

MODELING RELATIONSHIPS

Erosion scientists planning CREAMS, a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, in 1978 recognized the importance of concentrated flow erosion (USDA 1980). Consequently, CREAMS includes relationships for estimating this type of erosion for first- and second-order channel networks. CREAMS assumes steady state and peak runoff rate as a characteristic discharge rate to drive the equations.

The theory in CREAMS is based on the detachment equation

$$D = K(\tau - \tau_c), \qquad [1]$$

where D = detachment rate at a point on the channel boundary (mass/area $\cdot$ time),
K = a soil erodibility factor,
τ = shear stress at a point on the channel boundary,
and τ_c = critical shear stress for the soil.

A distribution for shear stress τ around the channel was assumed (Chow 1959) and combined with equation 1 in a detailed rill erosion model preliminary to CREAMS to compute change in the channel cross section for a steady discharge rate. The channel evolved to an equilibrium shape in a soil uniform with depth and eroded downward at a steady rate after an initial unsteady period as

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Table 1: Comparative Characteristics of Sheet and Rill Erosion, Ephemeral Cropland Gully Erosion, and Gully Erosion.

RILL EROSION	EPHEMERAL CROPLAND GULLY	GULLY EROSION
-Rills are normally erased by tillage; usually do not reoccur in the same place.	-Ephemeral cropland gullies are temporary features, usually obscured by tillage; reoccur in the same location.	-Gullies are not obscured by normal tillage operations.
-May be of any size but are usually smaller than ephemeral cropland gullies.	-May be of any size but are usually larger than rills and smaller than permanent gullies.	-Usually larger than ephemeral cropland gullies.
-Cross-sections tend to be narrow relative to depth.	-Cross-sections tend to be wide relative to depth. Sidewalls frequently are not well defined. Headcuts are usually not readily visible and are not prominent because of tillage.	-Cross-sections of many gullies tend to be narrow relative to depth. Sidewalls are steep. Headcut usually prominent.
-Flow pattern develops as many small disconnected parallel channels ending at ephemeral cropland gullies, terrace channels, or where deposition occurs. They are generally uniformly spaced and sized.	-Usually forms a dendritic pattern along depressional water courses, beginning where overland flow including rills, converge. Flow patterns may be influenced by tillage, crop rows, terraces, or other man-related features.	-Tend to form a dentritic pattern along natural water courses. Non dentritic patterns may occur in road ditches, terrace, or diversion channels.
-Occurs on smooth side slopes above drainageways.	-Occurs along shallow drainageways upstream from incised channels or gullies.	-Generally occurs in well defined drainageways.
-Soil is removed in shallow channels but annual tillage causes the soil profile to become thinner over the entire slope.	-Soil is removed along a narrow flow path, typically to the depth of the tillage layer where the untilled layer is resistant to erosion, or deeper where the untilled layer is less resistant. Soil is moved into the voided area from adjacent land by mechanical action (tillage) and sheet and rill erosion, damaging area wider than the eroded channel.	-Soil may be eroded to depth of the profile, and can erode into soft bedrock.

the channel adjusted from its initial shape to its equilibrium shape (Foster and Lane 1983).

Further analysis showed that relationships for the geometry of the equilibrium channel and its downward erosion rate could be analytically determined. These equations, functions of discharge rate, channel grade, hydraulic roughness, soil erodibility, and critical shear stress, are used in CREAMS to estimate concentrated flow erosion for the time before a channel erodes to a nonerodible layer. The equations were validated with data from rill erosion field experiments (Foster and Lane 1983). Rohlf and Meadows (1980) have also studied channel erosion with a model that calculates erosion at points around the channel's wetted perimeter.

As a channel having steady discharge rate widens after it reaches a nonerodible layer, erosion rate decreases. The rate of widening depends on the shear stress at the intersection of the sidewall and the nonerodible layer. Again the detailed model of rill erosion around the cross section was used to study the effect of the nonerodible layer. The results showed that the average erosion rate for time t could be computed from

$$E = \Delta W \, H_{sw} \, \rho_s / t, \qquad [2]$$

where E = erosion rate per unit channel length,
ΔW = change in width,
H_{sw} = height of the channel sidewall,
and ρ_s = mass density of the soil.

The change in width is given by

$$\Delta W = W - W_i = W_*(W_f - W_i), \qquad [3]$$

where $W_* = (W - W_i)/(W_f - W_i)$,
W = width at time t,
W_i = initial width,
and W_f = final width.

The normalized width changes according to

$$W_* = 1 - \exp(-t_*), \qquad [4]$$

where $t_* = t(dW/dt)_i/(W_f - W_i)$
and $(dW/dt)_i$ == initial rate that channel widens.

Equations 2 through 4 are functions of discharge rate, channel grade, hydraulic roughness, soil erodibility, and critical shear stress. The exponential decay in erosion rate implied by equation 4 was validated with experimental data from a field rill erosion study (Foster and Lane 1983). Accurate estimates of total erosion depends on accurate estimates of final channel width W_f. Equations were derived for W_f and were validated with data from channels ranging in width from rills to rivers (Lane and Foster 1980). Furthermore, channel erosion equations and concepts used in CREAMS are being used to analytically describe stream channel morphology (Osterkamp et al. 1983).

FURTHER DEVELOPMENTS

CREAMS was a first step. Its theory and equations are a starting point for a simpler, applied model useable by field technicians for estimating erosion by concentrated flow. The equations in CREAMS were based on the assumptions of steady discharge and uniform soil that restrict their application. Research needs for development of a more generally applicable model include

1. Use a detailed rill erosion model that computes erosion at several points around a channel cross section to study how channel erosion and channel shape vary with unsteady flow and a nonuniform soil profile.

2. Develop simple methods to estimate concentrated flow erosion. Such methods could consider drainage pattern, base level controls, runoff hydrology and hydraulics, soil conditions, cover, tillage, and other management factors.

3. Study the basic mechanics of erosion by concentrated flow. Current theory ignores the nonuniformity, and often localized characteristics, of concentrated flow erosion. The influence of basic soil strength properties should be determined. Field research is needed to evaluate parameter values so that SCS can apply a model to a wide range of climatic, soil, cover, and management conditions.

4. Validation data and testing are needed to insure that the models are sufficiently accurate for their intended applications.

SUMMARY

Seasonally ephemeral cropland gully erosion occurs in many tilled fields in areas where overland flow has converged in concentrated flow areas in natural depressions. These channels are tilled, often leaving them highly susceptible to erosion soon after tillage. Preliminary results from a recently initiated field survey show that erosion in these channels can be as great as sheet and rill erosion on some fields.

The Soil Conservation Service and Agricultural Research Service of USDA and other agencies are cooperating in research to obtain data and to develop methods to estimate erosion in these concentrated flow areas. Equations in CREAMS are a basis for some of this research. Further developments will include a better understanding of the erosion processes in these channels, simpler methods to estimate this erosion, parameter values to allow application of the methods to a wide range of conditions, and data and testing to show that the methods perform satisfactorily.

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RANGELAND EROSION AND SEDIMENTATION: RESEARCH NEEDS REVIEW

Clifton W. Johnson[1]

INTRODUCTION

Erosion and sedimentation research and application on rangelands have lagged behind that on cultivated lands because of low economic returns and the great difficulty and expense of effectively controlling erosion and sediment movement. However, there is an increasing concern for loss of soil productivity and environmental damage caused by erosion and sediment deposition. This paper reviews the proceedings of a workshop on estimating erosion and sediment yield on rangelands (U.S. Dept. of Agriculture 1982) and suggests additional research needs to support future watershed modeling programs. The workshop was very effective in providing a background on erosion research, especially development of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). Further, current methods of estimating erosion and sediment yield were presented. The recommendations prepared for the workshop proceedings were a most valuable summary of rangeland erosion research needs.

WORKSHOP REVIEW, COMMENTS, AND RESEARCH NEEDS

A variety of subjects were addressed in the 22 papers presented and discussed at the workshop as follows:

No. of papers	Subject
10	Universal Soil Loss Equation (USLE)
4	Sediment yield
3	Soil loss tolerance
3	Modeling erosion and sediment transport
1	Erosion and soil productivity
1	Rangeland management considerations

Individual workshop resolutions and recommendations, developed from the papers presented, were summarized in the report and are briefly reiterated herein. Also, comments on additional research needs and progress made since the workshop are included as follows:

1. Establish an interagency work group to adapt the USLE to rangelands.
   An interagency work group of 15-20 scientists met in April and August 1983 to plan data analysis and procedures for adapting the USLE to rangelands. Procedures for applying the USLE on rangelands similar to those developed for forest lands (Dissmeyer and Foster 1980 and Dissmeyer and Foster 1981) are scheduled for printing in 1984.

2. Accelerate research to adapt the CREAMS model for use on rangelands.
   The Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel 1980) has been applied on rangelands in Arizona, and data sets are being prepared to make additional tests on other western rangeland watersheds.

3. Determine realistic soil erodibility values by use of rainfall simulators.
   A thorough comparison of soil loss by using different large rainfall simulators (U.S. Dept. of Agriculture 1979) is needed to properly analyze data already collected. Rotating-boom rainfall simulators were used to determine USLE soil erodibility on a few soils in 1982 and 1983 at sites in Arizona, Idaho, Nevada, and New Mexico (Johnson et al. 1983, Simanton and Renard 1983, Nyhan et al. 1983). Soil erodibility of rocky soils, snowdrift areas, deeply cracked soils, soil crusts, and soils with high organic matter need further investigation. Also, spatial variability of soil properties related to erosion needs to be studied for application of rangeland watershed models.

4. Validate the USLE slope length and steepness factors on rangelands.
   Soil loss data from steep rangeland areas with widely ranging slope length is almost entirely lacking. Research is urgently needed to validate soil loss estimates on very steep rangeland slopes.

5. Improve the understanding of soil freezing and snowmelt processes which influence erosion and sediment movement.
   Studies are needed on rangeland plots and small watersheds to determine the influence of frozen soil, snowmelt, and winter rain on soil loss and sediment movement (Cooley and Robertson 1983).

6. Obtain urgently needed information on how to measure and describe vegetation characteristics for the USLE cover and management factor.
   Consistent methods of measuring vegetation and rock cover need to be developed. Recently developed photographic and computer techniques with supporting ground measurements should be used which are applicable on extensive and diverse areas. Reliable methods of measuring canopy height and density, rooting characteristics, litter, organic matter, and surface roughness are needed for many rangeland vegetation communities.

7. Promote research needed to quantify the effects of rangeland conservation practices, grazing, microtopography, brush, litter, and other irregularities.

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Rainfall simulators offer great promise in determining effects of rangeland grazing and conservation practices, reseeding, and brush control on erosion and sediment movement. However, standardized equipment, procedures, and plot size need to be established. Sites and conditions should include a wide range of soils, vegetation types, rock cover, surface roughness, grazing intensity, and land management.

8. Give more attention to establishing soil loss tolerance for rangelands.
   Generally, soil loss tolerances are set very low on most rangelands because so little is known about soil forming rates and harm from loss of thin topsoils (Wight and Siddoway 1982).

9. Conduct studies to compare naturally occurring and simulated rainfall.
   There are few ongoing studies relating natural raindrop size and rainfall energy and probability characteristics, as influenced by topography, elevation, aspect, and wind on rangelands (Tracy 1983). Presently used rainfall and simulator relationships are based on studies in the Eastern United States. Natural erosion plots should be installed at representative sites and operated for a minimum of 10 years to sample seasonal and storm-event soil losses to validate estimates by the USLE and other methods. These plots, like those in previous studies on cultivated lands, must be located for careful and long-term observation. Long steep slopes, frozen soils, snowmelt, and unusual surface roughness should be studied.

10. Determine usefulness of small plot simulators in estimating rangeland soil losses.
    Rill and interrill erosion from small and large rangeland plots under natural and simulated rainfall is poorly understood. Different application rates, drop sizes, fall heights, and areas covered make comparisons between simulations difficult. Studies should be conducted to compare erosion estimates obtained from large and small rainfall simulators.

ADDITIONAL RESEARCH NEEDS

Gully and channel erosion, sediment transport, and sediment deposition studies are needed on many rangeland areas to verify erosion and sediment components of complex watershed models now in use. Helicopter photography and recently developed, computer-based photogrammetric interpretations have been developed to aid in this research. Watershed sediment yield and sediment transport studies have proven valuable in modeling sediment production and need to be expanded.

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A REPLACEMENT FOR THE UNIVERSAL SOIL LOSS EQUATION (USLE)

G. R. Foster, J. M. Laflen, and C. V. Alonso[1]

INTRODUCTION

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) is the world standard for an equation to estimate sheet and rill erosion. No other current equation or procedure for estimating erosion approaches, as a whole, the USLE in ease of application, breadth of application, and accuracy. Yet the USLE has limitations because of its structure and its empirical origin. While the USLE provides reasonable estimates of average annual soil loss, it poorly estimates soil loss from individual and specific storms. One reason for this deficiency is that the USLE does not consider hydrology at specific points in time. Therefore, questions are asked about the validity of the USLE for climatic regimes like the Western United States where a very few storms produce the great majority of soil loss over a decade (Trieste and Gifford 1980). Estimates for short-term soil loss are important where practices are implemented for only a short time or where legal action might be involved.

Theory is well established that erosion is a function of several subprocesses including detachment by raindrop impact, detachment by flow, transport by splash, transport by flow, and deposition by flow (Cook 1936, Ellison 1947, Meyer and Wischmeier 1969, Foster and Meyer 1975). The USLE mixes and lumps these subprocesses over several factors that are, for the most part, independent of each other. For example, the USLE factor for the effect of slope length is

$$A = a \lambda^{m} \qquad [1]$$

where A = average soil loss for the slope length,
a = a coefficient,
λ = slope length,
and m = an empirically determined exponent.

The exponent m has varied in field experiments from 0 to 1 (Wischmeier et al. 1958). Theoretical and experimental studies suggest that this variation is a function of the relative contribution of rill erosion to interrill erosion, an effect described by equations having separate components for rill and interrill erosion (Foster et al. 1977). Meyer et al. (1975) and Young and Wiersma (1973) showed that the proportion of total erosion attributable to rill or interrill erosion varies greatly among soils and soil conditions.

A similar problem exists with lumped factor relationships for the effect of cover and management. The empirical equation for the effect of ground cover is (Laflen et al. 1981)

$$\phi = \exp(-bM), \qquad [2]$$

where ϕ = factor for ground cover effect,
b = a coefficient,
and M = percent ground cover.

The coefficient b has varied in field experiments from about 1 to 10 (Laflen et al. 1981), indicating a wide range in the effectiveness of a given percentage of ground cover. Theoretical analysis of how ground cover affects erosion suggests that ϕ is a function of the relative amounts of rill erosion and interrill erosion or a function of deposition of sediment behind mulch (Brenneman and Laflen 1982). The effective variation in b is inherent in equations having separate components for rill erosion, interrill erosion, and deposition.

Some crops are grown on beds less than a meter wide and separated by furrows on a very low grade. Intense erosion may occur on the beds, with much of the sediment being deposited in the furrows. The basic relationships describing erosion and deposition are quite different, but the USLE lumps them in this application. The structure of the USLE prohibits its application to slope lengths less than about 5 m (Foster et al. 1981), and therefore it cannot be applied to the short slope lengths of beds.

Sufficient justification exists for developing a more fundamentally based erosion equation or set of equations to replace the USLE. USLE technology has been used since about 1940 to estimate erosion, and it will continue to be used until at least 1990. Figure 1 shows our expectation of changes in technology for estimating soil loss. Theory and computational capabilities are now available to develop improved methods to estimate soil loss. W. H. Wischmeier and others recognized deficiencies while developing the USLE, but overall objectives for the USLE and computational methods available in the late 1950's and early 1960's significantly influenced the structure of the USLE (Smith and Wischmeier 1957). We are now ready to conduct research to develop appropriate equations and parameter values needed for a method to replace the USLE.

CRITERIA FOR A USLE REPLACEMENT

Requirements

A USLE replacement would likely meet the following requirements:

1. Apply to more situations than does the USLE, and be more powerful than the USLE; otherwise why replace it?

2. Be accurate for long term soil loss and soil loss from individual storms.

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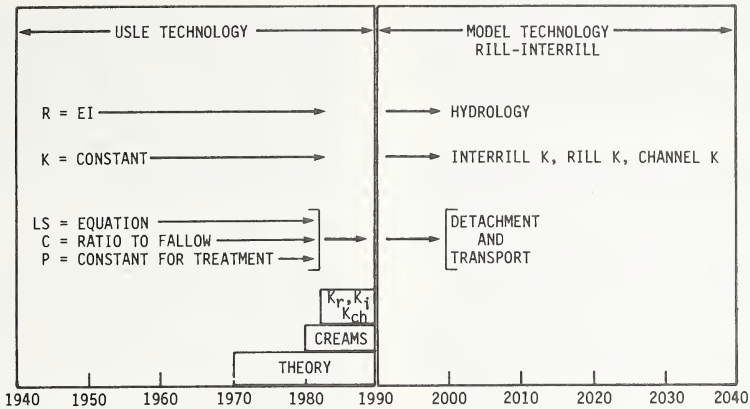

Figure 1. Comparison of USLE and model technology.

3. Be fundamentally based by having separate components for interrill erosion, rill erosion, sediment transport, and deposition.

4. Estimate both erosion and deposition along a nonuniform slope profile, and provide an estimate of sediment yield from a field sized watershed.

5. Estimate erosion and deposition by concentrated flow.

6. Estimate deposition in small impoundments.

7. Be practical for field use by conservation technicians.

Features

A USLE replacement would likely have the following features:

1. A set of equations rather than a single equation.

2. Programmed on a battery powered, portable computer (not a programmable calculator) that can be taken to the field and interfaced with a larger computer for transfer of programs, data files, and output. Alternatively, it might be used on a larger computer where its output is put in tables, charts, and graphs that can be used in the field.

3. Hydrologically based and driven by rainfall and runoff variables from a climate generator and a hydrology model.

4. Include a simple crop growth model.

5. Use storm amounts and peak intensities in its computations and not storm hydrographs to compute each storm's soil loss over a simulation period, sum and average these values for an estimate of average annual soil loss, and provide probabilities of severe erosion events.

6. Degree of complexity between the USLE and CREAMS, a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (USDA 1980).

THEORY

Analytical, closed-form erosion equations have been derived from the solution of the equations for kinematic flow and basic erosion processes for broad sheet flow (Hjelmfelt et al. 1975, Lane and Shirley 1978, Singh 1983) and for flow concentrated in furrows between parallel ridges (Meyer et al. 1983, Croley 1982). These solutions are for unsteady runoff and erosion immediately after the initiation of a steady rainfall excess. The solutions are usually for special cases like steady rainfall excess and slopes having uniform slope, soil, and cover. However, Shirley and Lane (1978) integrated the governing equations to develop an equation for soil loss for an entire storm by assuming that interrill erosion was directly proportional to a uniform rainfall excess rather than being proportional to the square of intensity, the usual case (Meyer 1981, Foster 1982). They did, however, obtain good results when their equation was fitted to data from field-sized watersheds.

Rose et al. (1983) derived steady state erosion equations and applied them to unsteady rainfall and runoff. Each step in the rainfall hyetograph and runoff hydrograph was treated as quasi-steady state. Steady state equations have also been given by Meyer and Wischmeier (1969), Foster and Meyer (1972, 1975), and Foster et al. (1977).

Use of either observed or generated hyetographs and calculated runoff hydrographs is presently judged to be impractical in a replacement for the USLE. Therefore, the best starting equation for a USLE replacement appears to be a theoretically derived steady state equation driven by empirical erosivity factors like the product of rainfall amount and maximum 30-minute intensity for an interrill erosivity factor and volume of runoff and peak runoff rate for a rill erosivity factor (Foster et al. 1977). Obviously this approach is less powerful than a fully dynamic model but more powerful than the USLE. CREAMS has clearly demonstrated the feasibility of this approach (USDA 1980).

PARAMETER EVALUATION

Once an equation or model form is chosen, experimental research must be conducted to determine parameter values for the equation or model to apply across a broad range of field conditions. This step is required; it must not be compromised by adapting parameter values from the USLE. Those values represent lumped erosion processes and therefore degrade the performance of a method based on separate equations for the fundamental erosion/deposition processes.

Two sets of parameter values will be needed, those for the hydrology component that generate rainfall and runoff erosivity values and those for the erosion/deposition components. Putting aside discussion of the hydrologic parameters, separate parameter values are required for interrill erosion, rill erosion, sediment transport, and deposition. This research is straightforward in some field situations. For example, these processes can be measured directly for the row sideslope-furrow systems studied extensively by Meyer (1984). The interrill and rill areas are distinct, and processes on the interrill areas are independent of those in the rills. However, interrill and rill areas are not distinct where tillage marks have little influence on flow patterns or where well defined rills are not present. Interrill and rill processes interact, and design of experiments to independently evaluate interrill and rill erosion parameters is not obvious for these cases.

Measurements of erosion on 12- and 23-m-long plots, standard lengths for many erosion studies by the USDA-Agricultural Research Service (ARS), are total soil loss from the plot, and this loss represents the integrated effect of all erosion processes occurring on the plots. Many erosion data are "noisy," and total soil loss estimates are inadequate for precisely evaluating parameter values for individual erosion processes (Lombardi 1979). The experimental approach by Hussein and Laflen (1983) of adding discharge at the upper ends of plots in a stepwise increasing fashion permits at least the conceptual separation of interrill and rill erosion. By this approach they were able to estimate separate interrill and rill erosion parameters for a conservation tillage system on two separate soils. Although their results followed the expected trends, the data were more scattered than expected. Determination of parameter values is a significant research challenge.

WHERE TO NEXT?

Lead technical personnel in the USDA Soil Conservation Service recently expressed the need for a more fundamentally based method to estimate erosion that would replace the USLE or at least supplement it. ARS has also recommended that such an equation be developed. Consequently, immediate plans and research initiated for its development are needed. The research could include the following steps:

1. Set a timetable. Probably at least 5 years but not more than 10 years will be required to develop the USLE replacement.

2. Choose an equation or model form. This step is required before initiation of field research to determine parameter values. Also, the step must be taken on the basis of current knowledge rather than waiting for research to improve our fundamental understanding of hydrology and erosion. Our current knowledge of fundamental erosion processes is sufficient to allow development of an equation or model that is one or two levels above the USLE.

3. Conduct field research to determine parameter values. This research will extensively use rainfall simulators and must provide information to allow the USLE replacement to apply to the range of conditions where the USLE is applied.

4. The result must be validated and if possible, confidence intervals assigned to estimates from the replacement. The best data for the validation will be from natural runoff plots and small watersheds, but do these experimental sites cover an adequate range of climate, soils, climate, topography, cropping, and management? Are the original USLE plots of much value for validation since cropping practices have changed greatly from the 1930's, 1940's, and 1950's, when the data were collected? Can erosion data from a constant intensity simulated rainstorm be related to the variable intensity of natural rainstorms?

SUMMARY

The Universal Soil Loss Equation (USLE), now 25 years old, is a widely used equation for estimating sheet and rill erosion. However, the structure and empirical origin of the equation limits it accuracy and applicability. Theory and computational capabilities are now available to develop significantly improved prediction equations that could replace the USLE. The replacement will be based on fundamental erosion processes of detachment, transport, and deposition, hydrologically based on both rainfall and runoff variables, will include a simple crop growth model, and will be driven by a stochastic rainfall generator. Research needs include selecting eqution forms, conducting experimental research needed to determine parameter values, validating the equations, and assigning confidence limits to output from the replacement. Five to ten years will probably be required to develop the replacement.

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SCS EROSION AND SEDIMENTATION ISSUES AND CONCERNS

William F. Mildner*

SCS activities are guided by the priorities established in the national program for soil and water conservation. They are (1) to reduce excessive soil erosion, which impairs agricultural productivity, on crop, range, pasture, and forest lands, (2) to conserve water used in agriculture and reduce flood damages in small, upstream watersheds.

This group's interest is focused mainly on priority 1 and the latter part of priority 2.

The SCS does not have sufficient resources to convince and assist every land owner and farmer to apply the necessary erosion control. Because resources are limited, we can work only on the most critical erosion areas. To focus on the worst problems, we must classify counties, land resource areas, or other units by erosion condition. To do this, we must account for all erosion.

In the past, it was adequate to count sheet and rill erosion and whatever gully erosion was present. Now, as we seek to focus our efforts on the most severe problems and to increase the efficiency of programs by linking program incentives directly to the erosion reduction the cooperator achieves; all the erosion on he landscape must be considered.

Erosion includes ephemeral gully erosion on cropland as well as sheet and rill erosion, major gullies, streambank erosion, and wind erosion.

Erosion is not the only item we need to measure. We also have to know sediment yield, by storm event as well as average annual yield, and yield to various locations such as to the edge of fields, to a stream, or to a reservoir.

To focus its efforts on the priorities, SCS needs the following tools:

1. A model to predict the effect of conservation measures on the grain-size distribution of the sediment yield.

2. A model for predicting sediment concentration in a stream in a small watershed for single storms.

3. A model for predicting sediment yield from single storms.

4. A model for predicting the magnitude and location of ephermeral gully erosion on cropland.

5. A model for predicting the magnitude and locations of erosion when water is applied during furrow irrigation.

6. A model for predicting field-size sediment-delivery ratio for fine and coarse-grained materials.

7. A model for predicting sediment yield for fine and coarse-grained materials from field-size areas.

8. A model for predicting the location in the field where critical erosion will occur.

9. A model for predicting the location where deposition will occur.

10. A model for predicting the rate of advance, rate of erosion, and sediment yield from large gullies.

11. Better methods of predicting the stability of channels.

12. Models to route sediment overland and in streams.

13. Models for predicting sediment distribution in reservoirs.

14. Research to ascertain the effectiveness of reduced tillage on ephermeral gully erosion on cropland.

15. Research to determine the erosion threshold and rates of erosion which can be expected from flow-through earth spillways.

Development of some of these models will be difficult and may result in a product which requires a large amount of input. Such models may not be entirely satisfactory for SCS use. Some models need not be extremely accurate; we would be willing to trade some accuracy for greater simplicity. In an effort to ease the transition from what might be called a research model to an operational model, it is expected that ARS and SCS personnel will work together to develop a final product.

If certain models were developed, some of the other models mentioned would not be needed. For instance, there would be little need for a model to predict sediment-delivery ratios from field-size areas if there was a suitable model to predict sediment yield from field-size areas. However, the former may be easier and, therefore, quicker to develop and could be an interim tool until the latter is available.

I have one additional comment, and that is about the interest in modifying the USLE. The USLE has been and is a very useful tool, but it has a number of limitations. The USLE was developed to fill a limited need with what was then state-of-the-art technology. With recent advances in computers and development of

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physical process models, the USLE could be regarded as a Model-T. The technology is now present to develop a replacement model which will predict deposition, sediment yield, and grain-size distribution of the sediment yield as well as erosion. It is my opinion that we should expend our major effort in developing a replacement model for the USLE by utilizing current technology rather than in continuing to patch an older model.

PLANNED GULLY RESEARCH AT THE USDA SEDIMENTATION LABORATORY

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INTRODUCTION

The USDA Sedimentation Laboratory at Oxford, MS is located in the Little Tallahatchie River watershed, which once contained some of the most elaborate and active gully systems in the United States. Selected gullies in this area were studied in detail by Woodburn (1949), Miller et al. (1962), and McDowell et al. (1967). Some of the results of these investigations, such as direct sediment production rates, were undoubtedly specific to the area because of the presence of highly erodible loessial soils. One probably general result, however, was the formulation of a conceptual model of gully development. It was postulated that the inception and early development of a gully is primarily a hydrodynamic phenomenon related to runoff, while later headward advance and widening of a fully developed gully is related to direct rainfall, slumping or block failure of saturated banks, and other general mass wasting processes. This conceptual model implies that process-oriented simulations of gully development must be based on research information about (1) direct rainfall intensity, impact, and duration effects; (2) hydrodynamic overland and gully flow effects; and (3) soil material effects. Not included in the original conceptual model, but intuitively obvious as a simulation requirement, is the need for a reliable prediction of probable locations of gully occurrence. For simulations of watershed response or for land management decision models, satisfying this last requirement should probably take precedence.

The soil material effects mentioned above are the most important factors in determining initial gully occurrence and spatial distribution; these effects are also important in determining the size, shape, and growth rate of the fully developed gully. Thus, except for gully inception, in which hydrodynamic processes dominate, surface and subsurface soil material effects control both gully growth rates and, ultimate, gully extent and configuration. Obviously then, soil material properties are the key factors to consider in developing a gully occurrence predictor. For developing a gully growth model, rainfall effects and overland flow effects must also be considered.

The planned research to be discussed in this paper is the effort at the USDA Sedimentation Laboratory to define soil material controls on the processes of gully development. These processes are the only rational basis on which to formulate gully models.

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PRIOR RESEARCH

The technical articles describing gully evolution and controlling factors and processes are largely restricted to morphometric studies. One of the earliest of these reports is the classical study by Ireland et al. (1939) of valley-side gully development in the piedmont of South Carolina. They identified four evolutionary stages, including (1) initial channel-cutting, (2) incision into weaker subsurface material, (3) grade adjustment, and (4) stabilization or natural healing. Of these four stages, stage (2) was the time of rapid and violent gully growth. Sidewall slumping was rapid as was headward migration of the overfall. Sediment production was also a maximum. Comparable results were reported by Bariss (1977) for gully development in the loess area of central Nebraska. For both studies, the stage of development was reflected by characteristic cross-section profiles. Comparable results for discontinuous valley-floor gullies have been reported by Brice (1966). The location of initial development of discontinuous valley-floor gullies has been related to areas of reduced vegetative cover (Graf 1979) and to areas of above average valley-floor slope (Patton and Schumm 1975). Such areas have been termed "critical locations" by Heede (1967).

Literature relevant to factors controlling or related to the rate of gully development is less abundant. Woodburn (1949) reported a rate of gully growth of 2 inches per year for areas of moderate relief. Relations between gully erosion and a rainfall intensity function (McDowell et al. 1967) and drainage area (Seginer 1966) have been documented. Both of these factors have been incorporated into the equation used by the U. S. Department of Agriculture Soil Conservation Service to preduct gully head advance. More complex relations have been presented by Thompson (1962) and by Beer and Johnson (1963). These relations have been discussed in more detail by Piest and Bowie (1974) and Piest and Grissinger (1980). Inherently such relations are empirical and have limited application. They reflect processes but are not process based, and they do not consider the stage or type of gully development.

Literature pertinent to gully processes is sparse. For all practical purposes, the only systematic study of gullying processes was conducted by R. F. Piest, J. M. Bradford, and coworkers. Their studies culminated in the articles by Bradford and Piest (1977) and by Bradford et al. (1978) in which they established that gully-wall instability and transport of the resultant slough from the gully system were two separate processes. Although hydraulic features determined the rate of slough removal from the system, gravity-type

failures determined gully wall stability-instability relations and hence sediment delivery to the transport system. This finding inherently means that long-term climatic factors and bank material lithologic properties that influence mass failure must be considered, in conjunction with individual storm characteristics, in evaluations of gully development and growth.

RESEARCH OBJECTIVES

The first objective planned for this research program is to determine the distribution of gullies on selected landscapes and to establish if the frequency of gully occurrence is associated with particular soil conditions, subsurface lithologic conditions, or site topographic conditions. The second objective is to identify processes and mechanisms of gully development, while the third objective is to define the patterns of gully development and evolution. The attack on the first objective will include examination of a large number of areas encompassing a broad spectrum of different soil, lithologic, and topographic conditions. Objectives two and three will involve the detailed study of certain sites selected during this examination.

GENERAL APPROACH

This study is based on the hypotheses that (1) gully development and evolution involve several processes and mechanisms, (2) that the specific types of processes and mechanisms are largely determined by the interaction of material properties with site-specific spatial conditions of each gully system, and (3) the intensity and magnitude of individual storm events will affect the rate of gully change but will not materially alter the types of processes and mechanisms. Specific and separate processes (1) modify the condition of the gully bed and banks, making the materials more susceptible to failure, (2) deliver slough to concentrated flow, and/or (3) remove material from the gully system, thereby completing the erosion cycle. Mechanisms involved in these processes include detachment by the erosive force of flowing water, by wetting and drying, by weathering, by raindrop splash, and by dispersion sediment entrainment, and transport. Other mechanisms involved are gravity-induced mass wasting, such as mud flows or failures produced by ground-water seep, slab failures with or without tension cracks, and slip surface failures. Obviously, failures due to some of these mechanisms will result primarily from individual storm events, whereas failures due to other mechanisms will result from the combined effects of hydrologic conditions for some preceding time. Observations have suggested that gully bed and bank materials that influence failure processes can be classified as individual lithologic units of the upland sequence, and these units are designated in our terminology as "lithologic process controls".

PROCEDURES FOR OBJECTIVE ONE

The spatial distribution of gullies is important, by itself, as one feature of the present landscape. More significantly, the distribution of gullies may indicate or suggest the nature of the controls of gully formation and development. The possible controls to be evaluated include soil type, the lithology of units immediately below soil depth (hereafter termed "subsurface units"), aspect, slope conditions (including average slope, slope inflections, and slope length) and relative position in the drainage net. The present land use will be defined and related to current gully enlargement. Past land usage will be documented whenever possible but will probably be fragmentary. Determining quantitative influences of land use on gully initiation will be difficult due to the absence of information relative to the time period of gully initiation (the late nineteenth to early twentieth century). The assumption will be made that all land surfaces studied were subjected at some past time to land use practices that had the potential to induce gully development.

The study areas will be selected to encompass a wide range of soil types and subsurface unit lithologies. For each type of gully lithology, one set of gullies will be instrumented for rainfall and runoff measurements. Gully distributions will be mapped from ASCS photographs, particularly the 1937, 1940-41 and 1949-50 photographs, and from existing soil surveys. The soil survey maps will also be used to construct the drainage nets. Topographic maps will be used to evaluate slope conditions. General lithologies of subsurface units will be established from geologic literature and, if necessary, by subsurface investigations. All map data will be obtained using the Altek Digitizer, and the data will be adjusted to constant scale after conversion to digital form. Analysis will involve primarily spatial statistics. All study areas will be in northern Mississippi.

PROCEDURES FOR OBJECTIVE TWO

This objective includes (1) identification of processes and mechanisms of gully development and (2) evaluation of process and mechansim controls, including soil, subsurface unit, aspect, slope and relative position controls. Rainfall and runoff data will be collected for the instrumented gullies, but resource limitations prohibit this activity for all study areas. For the study sites not so instrumented, local weather records will be employed to estimate runoff using rainfall-runoff relations developed for the instrumented sites.

Gully bed and bank materials will be classified as units of the upland sequence, and gully morphology will be quantified by surveying or photogrammetic techniques. The types of failures and the associations of failure types with individual lithologic units, or sequences thereof, will be

identified by field observation. Bank conditions, particularly the prevalence of tension cracks, will be described and seepage zones will be located. The susceptibility of bank materials to gravity-induced failure will be evaluated using a dimensionless stability equation similar to that used by Bradford and Piest (1977), and including bulk unit weight of bank material, critical bank height, tension crack depth, bank material cohesion, friction angle, and bank slope angle. For this analysis, the Iowa borehole shear tester will be used in situ to evaluate bank material cohesion.

The suseptibility of gully bank materials to individual particle detachment will be evaluated as the maximum noneroding velocity as measured by the pinhole procedure, or modification thereof. Disturbed and undisturbed samples of each lithologic unit will be collected at each study site and analyzed for pH, water-soluble and/or exchange chemistry, bulk density, and particle size. Mineralogical and surface area analyses may be required. Empirical analyses will be used to develop possible relations between material composition properties and slope stability and/or detachability. Soil-water sensors will be installed at selected locations to quantify the soil-water variable.

PROCEDURES FOR OBJECTIVE THREE

The ergodic hypothesis, as applied in geomorphic studies as a space for time substitution, has been routinely used to construct patterns of gully development. This is entirely morphometric and, by itself, is of questionable value in process-oriented studies or modeling efforts. For this objective, the morphologies of various gullies and morphometric changes through time will be mapped using ASCS aerial photographs and historic records. Additionally, process and mechanism controls, previously identified, will be evaluated for each gully system. In essence the process and mechanism controls will be used as surrogates for the evolutionary processes and mechanisms, and the evolution or development of gully patterns will be evaluated in relation to the interaction of process with age. Inherently in this evaluation, the utility of the ergodic assumption for this application will be evaluated.

SUMMARY

The simulation of gully occurrence and development is an essential part of any watershed response modeling effort. Progress in such efforts has been constrained by the lack of knowledge about the individual mechanisms of gully bed and bank instability. These failure mechanisms are complex, involving the relative balance between the several erosive forces and the several strengths of the bed and bank materials resisting erosion. In this sense, a bed or bank material has several individual strengths, each of which resists failure by a specific mechanism. At present, little is known about actual failure mechanisms in the field. How are failure frequencies for individual failure processes related to flow and sediment conditions? Do general climatic conditions influence failure frequencies independently of flow conditions? What soil properties influence failure mechanisms and how can they be most economically estimated? How do failure processes vary with the stage of gully development? The absence of answers to these and related questions illustrates the main thrust area to be addressed by this research.

Modelers will benefit from improved delineation of critical processes and from definition of the distribution of process controls. This integration of geomorphic data with model development will yield models that will aid conservationists in effective planning and management of upland natural resources. In order to answer fully all general modeling needs, research comparable to that described here should be conducted in each physiographic region.

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PHOTOGRAMMETRY: A TECHNIQUE FOR MONITORING GULLY EROSION

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INTRODUCTION

This document presents a progress report on a cooperative research project between the USDA-ARS, Southern Piedmont Conservation Research Center and the Geography Department, University of Georgia. The project involves the development and testing of photogrammetric techniques for monitoring soil erosion due primarily to gully formation. Since the ongoing research is not complete, this report will deal primarily with the description of the project and the methodology being used. Preliminary findings will be summarized; however, no major conclusions will be attempted at this time.

The purpose of this report is to familiarize interested scientists with this research and some of the possibilities available to them. Photogrammetry has been widely employed by many agencies as a technique for topographic mapping but has not been widely used as a research tool in erosion research. The objective of the investigations reported herein will be to introduce photogrammetry as a viable method to produce maps for monitoring erosion and, possibly, for site or structure planning and design.

Basic Concepts

Photogrammetry is a method which can be used to obtain highly accurate X, Y, Z terrain coordinates of fragile erosion surfaces recorded on stereophotographs. Given close-range photographs from two or more dates bracketing a storm event, the volume of eroded material can be determined. Two approaches are possible: (1) analog photogrammetry and (2) analytical photogrammetry. Analog photogrammetry techniques, while versatile, normally require the use of costly stereoplotters and the services of a trained photogrammetrist. Output may be either detailed topographic maps or sets of X, Y, Z coordinates from which digitial terrain models (DTMs) of the study area can be constructed. Analytical photogrammetric techniques, on the other hand, involve the measurement of image coordinates and their transformation into X, Y, Z terrain coordinates by computational procedures. Both the analog and analytical approaches can be used with photographs obtained from metric or nonmetric cameras.

A metric camera is one which has been calibrated to precisely determine the camera focal length, the geometric location of fiducial marks in the focal plane (which in turn define the geometric center of the photograph), and the distortion characteristics of the camera lens. Because the geometric characteristics of photographs obtained with metric cameras are known, the recovery of X, Y, Z terrain coordinates to extremely high accuracies is possible. Unfortunately, however, metric cameras range in price from about $25,000 for the medium (10.5 x 13 cm) format models used in close range applications to over $100,000 for large (23 x 23 cm) aerial cameras.

Nonmetric cameras, on the other hand, include 35- and 70-mm cameras which can be purchased at camera stores for as little as a few hundred dollars, and are available to most anyone. Thus, the investment required for nonmetric camera equipment is minimal. Such cameras, however, are not calibrated and their lenses may produce rather significant radial distortion patterns which must be minimized in the data adjustments procedures of photogrammetry. Consequently the accuracies of coordinates derived from nonmetric photographs will normally be lower than those from metric photographs. However, because the accuracy of coordinates is generally proportional to the distance between camera and the object, the camera stations can be positioned to satisfy predetermined accuracy requirements.

The accuracy of the Z coordinate (or spot height) values is the critical parameter for soil erosion studies and must be on the order of a few centimeters. In photogrammetric applications the accuracy of spot heights is normally specified in terms of root-mean-square error (RMSE), which is a statistical measure indicating that 68 percent of the coordinates can be expected to be correct to within the specified value. When vertical photographs are recorded, the $RMSE_Z$ is often determined by the geometry of the camera stations to the ground.

METHODOLOGY

Study Areas

This research project involves the use of two areas at the Southern Piedmont Conservation Research Center, Watkinsville, GA. An area (site 1) on a small stream, known as Lampkin Branch, was employed in the measurement of stream channel erosion from vertical stereophotographs. The second area has two sites: one (site 2) at which horizontal or "terrestrial" photography is being used to assess roadbank-type erosion and another (site 3) where a gully forming at the nodal point of a watershed is being monitored with vertical photography. At each site a number of ground control points (GCPs) were installed prior to photographing.

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Ground Control

The ground control provides a common reference system within each individual site from which stereomodels recorded on different dates can be rectified by analytical procedures. Ground control points in the sites consist of between 13 and 20, capped, 1-m iron stakes distributed throughout the stereomodel areas and driven into the soil to a depth of approximately 85 cm. The white caps of 55-mm diameter are designed to provide an image target of 0.12 mm at the nominal photo scale. A black dot placed in the center of each cap serves as a pointing mark during the field survey.

The X, Y, Z terrain coordinates of the control points are established in local coordinate systems using a thedolite and conventional triangulation and trigonometric surveying procedures. The local coordinate systems are each based on three permanent reference points located at stable places in the site so that in the event the control stakes are removed or displaced, new points can be quickly established. The coordinate errors in the local coordinate system for all ground control points averaged less than $\pm$ 1.5 mm in X, Y, and Z, or approximately 1 part in 10,000.

PHOTOGRAPHIC CONSIDERATIONS

To record vertical stereophotographs at close range, camera stations should be established at a predetermined horizontal interval (that is, the "base"). The height of the camera above the ground determines the scale of the photographs, which may be calculated with the well-known equation

$$\frac{f}{H} = \frac{1}{SF} \tag{1}$$

where f is the focal length of the camera lens; H is the vertical distance from the camera station to the ground; and SF is the scale factor of the negative image.

It is important to establish the nominal negative scale of the photographs at the outset of the project so as to permit the determination of the ground area covered by the stereomodel and the appropriate size for caps used to mark ground control points (GCPs). Normally, the study sites are rectangular areas of a few meters to a side and are limited to one stereomodel. The ground area which forms the stereomodel is a function of the photo scale, film format, and camera spacing or base-to-height ratio.

Prior to recording the photographs, 50 to 100 or more point markers consisting of small white cardboard disks or steel washers should be distributed to adequately define the terrain within the study site. These markers, like the GCP caps, must be of sufficient size so as to represent a diameter of approximately 0.1 mm at the negative scale of the photographs. The purpose of the markers is to provide a dense network of points which can be readily identified and measured on all photographs.

Recording of vertical photographs is relatively straightforward. The camera is positioned at predefined camera stations, approximately leveled so as to ensure a near vertical photograph and the exposures made. It is desirable to avoid strong shadows or glare. After the film has been developed, the original negative must be enlarged by a factor of 5 to 10 and printed as either paper or film positives. In the printing operation care must be taken to level the enlarger, center the negative, and retain the edges of the frame so as to ensure the geometric fidelity of the enlarged images.

The taking of terrestrial photographs is similar to that of vertical photographs in that the camera stations are predetermined according to the desired photoscale and base distance. The camera, however, is either attached to a tripod or hand held and aimed horizontally at the object. This creates an image which is geometrically dissimilar to that of a vertical photograph. In vertical photography, for example, the X-Y plane is imaged and depth is seen as variations in Z, whereas with terrestrial photography, the photo is of the X-Z plane and depth is in the Y direction.

DATA REDUCTION PROCEDURES

In analytical photogrammetric application, it is necessary to carefully measure the image coordinates of terrain points. Normally, such measurements are undertaken by a skilled technician using a monocomparator or stereocomparator and provides X, Y image coordinates reliable to within a few micrometers. Computational procedures required to derive the desired X, Y, Z terrain coordinates are then conducted on a mainframe or minicomputer.

A standard cartographic digitizer is employed to measure image coordinates on film or paper print enlargements. The enlarged prints which comprise a stereopair of the study site are examined; and the GCPs and marked points, sequentially annotated. All annotated points on each photograph are then measured with the aid of the digitizing system. Three rounds of measurements of 100 points on each photo of a stereopair can be completed within 1 1/2 to 2 hours. With large digitizing tables having a resolution of 25 μm (0.001 inch), a precision of about $\pm$ 30 μm is obtained. For smaller tablets with resolution of 0.05 to 0.1 mm, the precision is about $\pm$ 0.19 mm. It is of interest to note that the precision of coordinate measurement on the enlargement divided by the enlargement factor yields the precision of measurement at the negative scale. Thus, a x 7 enlargement typically yields values at the negative scale ranging from $\pm$ 4 to $\pm$ 27 μm, depending on the resolution of the digitizer employed. Experience to date indicates that the accuracy of the final computed terrain coordinates will not vary in direct proportion to the differences in measurement precision obtained from digitizing systems.

The measured x, y image coordinates are input to a computer, transformed to coordinate systems having their origins at the geometric centers of the photographs, and refined to correct for systematic distortions. These refined image coordinates of the GCPs are then used to resect each photo of the stereopair in order to establish the position and orientation parameters of the camera system at the time the photos were recorded. The resection programs employ the standard collinearity equations given below:

$$x = -f \frac{m_{11} (X-X_o) + m_{12} (Y-Y_o) + m_{13} (Z-Z_o)}{m_{31} (X-X_o) + m_{32} (Y-Y_o) + m_{33} (Z-Z_o)}$$

$$y = -f \frac{m_{21} (X-X_o) + m_{22} (Y-Y_o) + m_{23} (Z-Z_o)}{m_{31} (X-X_o) + m_{32} (Y-Y_o) + m_{33} (Z-Z_o)} \qquad (2)$$

where f is the camera's focal length; x, y are the refined image coordinates of the GCPs; X, Y, Z are the known coordinates of the GCPs in the ground coordinate system; X_o, Y_o, Z_o are initial approximations of the camera station coordinates in the local ground system; and m_{11}, m_{12}, etc. are rotation elements which must be determined by the simultaneous solution of the collinearity equation for five or more GCPs. An iterative least-squares solution of these equations for each photo of the stereopair establishes the camera positions (X_o, Y_o, Z_o) and orientation angles at the time the photographs were recorded.

In a final step, the unknown X, Y, Z terrain coordinates of the point markers are determined by a space intersection procedure. Using the inverse of the collinearity equations with the previously determined position and orientation values for the camera, rays are mathematically projected to the ground through the lens of the camera and the image coordinate locations of the measured points. Conjugate rays to the same object point from the two camera stations will intersect in space and define the X, Y, Z terrain coordinates of the object point. Thus, the X, Y, Z coordinates in object space can be determined for each point having measured x, y image coordinates on both photos of the stereopair.

APPLICATION OF METHODOLOGY

Site 1

Lampkin Branch drains a 230 ha gauged watershed of mixed land use. Because it was anticipated that changes in the channel due to storm runoff would be most noticeable at the meander bends, the study site was located at one bend upstream of the weir. The approximate vertical relief of the site above the weir was 1.5 m.

A standard Honeywell Pentax 35-mm SLR camera equipped with a Bushnell wide-angle lens (f = 21 mm) was employed to record six stereopairs of vertical photographs. These photographs were recorded before and after storm events from a platform 9.5 m above the stream. At the outset of the projects, 18 GCPs were established within the 12.7- x 11.1-m study site to an accuracy of $\pm$ 1.5 mm in X, Y, and Z. Then, before each set of photographs was exposed, an additional 80 to 90 point markers were distributed throughout the site. Subsequent reduction of image coordinate measurements by the previously described analytical procedures provided RMSE values of approximately $\pm$ 4 mm in X and Y and $\pm$ 6 mm in Z.

The 100 or so randomly distributed points in each model were interpolated with computer graphic routines to construct uniformly gridded DTMs with Z values at 0.25 m spacing. Further processing by computer permitted the development of contour maps and profiles of the study site for each date. These were used to assess changes in the channel. In addition, the DTMs were placed in register and changes in elevations at the grid intersections determined. From these changes the volume of sediment eroded or deposited in the stream channel with reference to a fixed datum was easily calculated. Three-dimensional perspective views of the study site and of the changes were constructed.

Site 2

A small (approximately 3 x 3 m) site was establish to simulate roadbank-type erosion. Soil was loosened and shaped to a 45-degree slope. Ground control consisted of 6 iron stakes and an aluminum control frame which contained 12 surveyed points.

Both hand held and tripod mounted 35-mm terrestrial photographs were taken to monitor the rate of gully formation. Before exposing the photographs, approximately 200 1-inch-diameter steel washers painted white were distributed for use as observed point markers. The data reduction procedures described above were employed to derive X, Y, Z terrain coordinates from the photographic data. Insufficient data are available for this report to assess results. It does appear, however, that accuracies of similar magnitude to those obtained in the stream channel site may be had.

Site 3

Site 3 is located near site 2 at the nodal point of 15-ha watershed, where a shallow gully had previously been forming. The soil was loosened and smoothed with a disk harrow. Ground control points in this 3- x 3-m site consist of 16 iron stakes arranged in a grid pattern. Vertical stereophotos were taken from a platform (H = 3.5 m) constructed on a Blue Hi-Boy crop spraying rig. Again, insufficient data are available for this report to assess results.

SUMMARY

We have demonstrated the relative ease of making accurate, repetitive measurements of a small area using photogrammetric procedures. Once preliminary preparations have been completed for a site

(that is, the ground control established), the point markers can be distributed and the photographs recorded in about 1 hour. Measurement and reduction of approximately 100 points on photographs forming a stereopair take less than 2 hours (not including graphics).

We believe that this methodology is very suited for obtaining data required in developing predictive models for gully and channel erosion and, perhaps with the aid of a helicopter or low flying aircraft, for large scale topographic mapping of field-size study area and to site assessments. Further development of photogrammetric techniques as applicable to serving conservation practices and goals (that is, erosion model development, and farm pond and terrace design) is the subject of cooperative research by the University of Georgia; Agricultural Research Service, Southern Piedmont Conservation Research Center; and the Soil Conservation Service.

NEEDED EXPERIMENTAL BASES FOR PROCESS-ORIENTED ERODIBLE CHANNEL MODELS

Neil L. Coleman[1]

INTRODUCTION

Channel erosion is the means by which drainage nets are imposed on land surfaces. It is the most noticeable part of the geomorphological sequence that begins with the dissection of uplands and ends with peneplanation. Mathematical modeling or numerical simulation of channel erosion is the most essential and problematical aspect of the simulation of catchment response to new climatic conditions or new land use conditions. Channel erosion simulation demands the consideration of hydrological, hydrodynamic, and geological components and their interactions. True process orientation of a model demands detailed knowledge of the processes associated with each of these three components, and this knowledge is mostly lacking. This paper is an overview of the kinds of experimentation needed to provide this knowledge in some of the more crucial situations in channel erosion modeling.

THE NATURE OF A DRAINAGE NET

The various aspects of both channel erosion experimentation and erodible channel simulation can be best viewed by organizing them according to the systematic nature of a drainage net. A drainage net consists of rills, gullies, and stream channels. These are differentiated on the basis of their relative sizes and slopes, and on the frequency with which they discharge significant flows. Rills, gullies, and the smaller stream channels are usually ephemeral, and their flows correlate closely with local rainfall. Larger stream channels have appreciable base flow, as well as hydrographs that are not so immediately responsive to individual storm episodes. Larger lowland rivers tend to have hydrographs with time scales similar to those of weather front occurrence rather than to those of individual storm occurrence. The ultimate lowland rivers, such as the Missouri, the Mississippi, and the Amazon have hydrographs with time scales that approach seasonal magnitude.

Rills and gullies characteristically exhibit sheer walls, banks, steep gradients, and frequent headcuts. Flows are intermittent and generally in the rapid-turbulent regime (Robertson and Rouse 1941), although in extremely shallow flows the restriction in depth and associated vortex stretching may make the flow approach the rapid-laminar regime. Since rills and gullies are the initial incision of the drainage net on the landscape, the sediment carried by rill and gully flows often contains significant proportions of newly detached aggregates, clay and silt particles, and lesser proportions of sand and gravel.

Upland channels and streams exhibit sheer to steeply sloping banks, relatively steep bed gradients, and quite large headcuts associated with resistant stratigraphic features that are intersected by the channels (Grissinger and Murphey 1981). Flows are intermittent and are usually in the tranquil-turbulent regime during rises, peaks, and early recession, and in the rapid-turbulent regime during late recession. Soil materials carried are usually in the form of a wash load consisting of clay and silt, either in primary or aggregated particles. Other sediments carried in significant proportions are sand, which moves both in suspension and as bedload, and gravel, which may move in appreciable amounts as bedload. Upland channels erode and continuously modify their gradients and channel shapes by a sequence of headcut migration and bed degradation followed by massive local bank failure (Thorne et al. 1981) caused by the undercutting associated with bed degradation.

Lowland rivers are the recipients of the water and sediments brought down by the upland stream channels from the source erosion areas. Lowland rivers exhibit moderate to nearly flat gradients, with banks alternating between sheer cutbanks and gentle slipoff plains or point bars. They have a meandering planform which is the result of an energy dissipation process during base level approach. This planform should not be confused with the geologically controlled bendway planform typical of upland stream channels. Lowland river flows are in the tranquil-turbulent regime and frequently have large, relatively steady flows capable of transporting large amounts of sediment.

PROCESSES COMMON TO ALL ERODING CHANNELS

The sedimentationist is often struck by the remarkable similitude of processes that exist, despite manifest scale and regime differences, for all eroding channels. In all channels, regardless of type, boundary shear stress exerted by the flow detaches and sets into motion sedimentary particles, whether they be primary soil particles or clastics like sand and gravel. The shear stress also induces turbulence generation which activates diffusion processes and flow resistance or energy dissipation processes. The energy dissipation is in turn augmented by geometric boundary variation, which causes secondary flow. The significance of each process varies with channel size and gradient, but the variation is one of degree only; hence, in a certain sense, it can be argued that like rills, small channels are,

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in fact, scaled-down physical models of large channels.

The processes of shear stress exertion, turbulence generation, diffusion, and flow resistance generation all are important in the computation of turbulent boundary layer flows. Such computation (or numerical simulation) is routinely employed for investigating flows over relatively simple configurations like airfoils or ship hulls; however, even there it is regarded as fraught with unsolved problems. In erodible channels even greater problems exist because of the presence of a feedback process--the flow modifies the channel geometry and the channel in turn modifies the flow. This feedback process manifests itself in rills and gullies as headcut migration and downcutting; in upland stream channels as headcut migration, downcutting, massive bank failure, and bedform propagation; and in lowland channels as meander generation, bedform propagation, and local scour.

SPECIFIC CHANNEL EROSION MODELING SITUATIONS FOR THE VARIOUS PARTS OF A DRAINAGE NET

All the foregoing material has been presented to provide a unified view of the drainage net context in which a process-oriented erodible channel modeling effort must be placed. Within this context, some specific experiments in support of this modeling effort may be discussed.

The rills, gullies, and small stream channels high in the drainage net present an extra complexity because their boundary geometries are complex and convoluted, and their flows are ephemeral and, hence, unsteady. Little application of fluid mechanics principles to ephemeral unsteady flows is possible at present. Experimental capability is mostly confined to attempting to find fundamental principles of steady flow in rills and other upland channels. Experimental studies have been made of the process of rill formation on surfaces of various slopes (Meyer et al. 1975) and on the sediment transport capacity of rills, furrows, and similar channels (Willis 1971, Meyer et al. 1983). Research is needed on the detailed mechanics of soil particle detachment by flow in rills, and on aggregate particle durability during downslope transport. Little if anything has been done on the former topic, while some preliminary studies (Rhoton et al. 1983) have been done on the latter. Knowledge of aggregate detachment and transport is essential for simulating both the actual development of rills and the removal of productive topsoil from sediment source areas.

Sediment transport by rills to downslope gullies and stream channels is not confined to material eroded from the rill boundary but also includes material, from interrill erosion, that is detached by raindrop impact and transported to the rills by interrill flow and splash.

Detailed studies of the mechanics of raindrop impact have been made (Mutchler and Young 1975); but because the results of these investigations do not currently lend themselves to inclusion in simulation efforts, much research remains to be done. Both rills and gullies, by virtue of their shallow flow depths and rapid-turbulent flow regimes, represent somewhat special fluid mechanics situations with a high probability that special sediment transport relationships, unlike those that apply to rivers, are significant. Evidence tending to support this view has been presented by Meyer et al. (1975) and by Meyer et al. (1983). Before valid rill and gully erosion simulations can be developed, a comprehensive research program must be carried out on the characteristics of velocity, turbulence, and shear distributions in very shallow rough-boundary flows. This program should be aimed at expanding and generalizing the results of Foster (1975). This research should be oriented toward the development of particle transport prediction methods and coordinated with the aggregate particle detachment and durability investigations mentioned above.

Upland channels, with their failure-prone banks, geologically controlled migrating headcuts, and tranquil-turbulent peak flows present a highly interactive system of soil mechanics and fluid mechanics principles. During recession, on the other hand, because of their rapid-turbulent flows they present some similarities to the rill and gully situations discussed above. Important erosion-sediment transport processes in these channels include all the processes treated in classical river mechanics (Graf 1971), such as velocity, turbulence, and shear distribution and sediment suspension mechanics. However, two other even more important processes act in these channels. These are the processes of bank failure and the processes of flow resistance variation due to unsteady flow. Bank instability and failure has been investigated in some detail by Thorne et al. (1981), and failure prediction methods, based on soil mechanics principles, are available which can be readily incorporated into simulations of the morphological changes of upland stream channel shape. Flow resistance variation due to unsteady flow is a more difficult problem, the solution to which is essential to adequate flood wave routing in upland channels. A program of field observation of flow resistance in unsteady upland channel flow was conducted by Coleman (1962); however, the results obtained could not be generalized for use in modeling. A later attempt at laboratory study (Coleman and Wilson 1981) resulted in failure to generate any flow resistance data for unsteady flows. Thus, this particular essential field of experimentation remains completely open, and upland channel flood wave routing remains without one of its necessary process foundations.

Both upland channels and lowland channels and rivers share the need for a flow resistance relation for use in flood routing models. While

the problem of resistance relations for unsteady flows is perhaps more crucial in the very intermittent upland streams, the problem of bedform-related flow resistance is equally important in both upland and lowland channels. Alam et al. (1966) developed a not particularly successful predictor for the resistance coefficient for steady flow in alluvial channels with propagating bedforms. At about the same time Vanoni and Hwang (1967) found a relation between the length and height of bedforms and the resistance coefficient that had the same functional form as the Nikuradse (1933) rough pipe formula. This relation was found in flume experiments using stationary models of bedforms. It remained for the author (Coleman 1983) to provide conclusive proof that such a formula could apply to actual propagating bedforms, using statistical measurements of these bedforms to characterize the hydrodynamic roughness height needed in the resistance relationship. This proof, however, does not include the production of a useful engineering resistance coefficient predictor; so this area of research, too, is open for improvement and significant contribution to process-oriented erodible channel simulation.

General experimental requirements for the ultimate in process-oriented simulation of both upland and lowland erodible channels include further investigations of the processes of sediment suspension, the characteristics of curvilinear flow in bendways and meanders, and the stochastic nature of the turbulent shear stress both in the flow and at the channel boundary. Some preliminary results of experiments on turbulent boundary shear stress have been presented by Alonso and Coleman (1981) for the case of a smooth rectangular channel. These results should be extended over a wider range of boundary conditions, channel shapes, and flow magnitudes. A recent work (Coleman 1981) has updated and clarified the feedback relation between suspended sediment concentration and local flow velocity, but more experimentation is needed to provide a universal suspended sediment concentration predictor.

CONCLUSIONS

The kinds of erodible channels in a drainage net have been described, and both their differences and their common features have been noted. Within the context of the drainage net, important specific instances have been suggested where more research is needed to provide a foundation for process-oriented erodible channel simulations.

For support of rill simulation, priority should be given to studies of soil particle detachment and of the durability of aggregated soil particles as they are carried by runoff through the drainage system network. Also, special studies of shallow flow hydrodynamics should be made to define the characteristics of rill flow and rill sediment transport.

In upland channels, the two most important problems are incorporating bank failure and channel shape change predictions into models and introducing flow resistance relations for the ephemeral flows commonly observed. The latter accomplishment is essential for adequate floodwave routing.

In both upland channels and lowland channels, a predictor for flow resistance associated with propagating bedforms is needed for floodwave routing. A universal predictor for suspended-sediment concentration is also needed to complete the experimental foundations for mathematical modeling of erodible channels and rivers.

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A CONCEPT FOR MODELING DEPOSITED SEDIMENT DISTRIBUTION IN RESERVOIRS

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INTRODUCTION

Small impoundments are designed and constructed to serve specific or multiple purposes, including trapping sediment, flood control, water storage for irrigation, water for livestock, fish production, recreation, domestic water supply, and others. In order to satisfactorily design and manage water impoundments to meet these objectives it is necessary to have some control over inflowing sediments. Most agricultural reservoirs trap sediments, other debris, and associated nutrients and other chemicals.

Sediment and debris trapping basins are significant components in a watershed drainage network, and problems relative to their design, operation, and maintenance are important. Their importance is of particular importance when large yields of fine sediments consisting of clays and silts are expected. Accurate performance predictions in terms of a trap efficiency and deposited-sediment spatial distribution is required to avoid overdesign and excessive construction costs.

The sediment trap efficiency of a reservoir is the proportion of the inflowing sediment that is trapped in the reservoir. Current methods recommended by the Soil Conservation Service, USDA, for predicting trap efficiency for reservoirs are based on the work of Brune (1953), who analyzed data from 44 reservoirs. This research was extended by Dendy (1974), who analyzed records from 17 small structures in the same manner. Data for these studies were obtained by measuring the water and sediment outflow. The reservoirs were surveyed and the sediments sampled, usually at 5-year intervals, to determine volume and weight of the deposited sediments to the sum of the weights of the deposited sediment and the weight of the outflowing sediments. Brune developed a graphical relationship between the trap efficiency and the reservoir capacity average annual inflow. This ratio can be interpreted as the average water residence time, in years, for the reservoir. Dendy developed an empirical expression for this graphical relationship. The field data show some degree of scatter, and Brune plotted envelope curves in addition to the median curve relating trap efficiency with residence time. The Soil Conservation Service has utilized the upper envelope curve to predict the trap efficiency of primarily coarse-grained sediments and the lower envelope curve for fine-grain sediments. For small reservoirs with short residence times, this scheme is quite unsatisfactory and often does not predict true trap efficiency.

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The objective of this paper is to propose a method to predict deposited sediment distribution and trap efficiencies of reservoirs. This method uses a sediment transfer function concept based on sound physical principles for reservoirs with simple morphometry. The resulting model should be capable of simulating the outflowing sediment particle size distribution, the spatial distribution of the deposited sediments, and the size distributions of the deposited sediments.

Approach

The analytical form of a sediment transfer function for a reservoir can be developed in terms of the probability of a particle of a given size passing through the reservoir. For very fine sediment particles (less than 0.1 micron), the probability of their passing through a reservoir with a continuous water discharge is unity. For large sediment particles (coarse sand and larger), the probability of their passing is zero. For the intermediate sizes the probability of passage is between these two extremes. Therefore, a functional relationship is required which predicts the probability of transfer (passing), $t(D)$, for any given size sediment particle, D, in a given resevoir flow situation.

Once established, the probability of the sediment transfer function can be combined with the size distribution function of the sediment suspended in the inflow and the sediment concentration of the inflow to predict the size distribution and concentration of suspended sediment at any point in the reservoir. This procedure will be outlined in this paper.

From a theoretical analysis of the physical processes, the probability of particle transfer through the reservoir is of the mathematical form

$$t(D) = ECP - (funct(B,S,Sc,Re)$$

where

$B = wL/\Delta$; a dimensionless partial fall velocity;

$S = L/h$; a characteristic scale ratio,

$Sc = v/\Delta$; the Schmidt number,

$Re = Uh/v$; a characteristic Reynolds Number,

$w(D) = \frac{gD^2}{18v} \frac{(\rho-\rho_p)}{\rho}$; particle fall velocity,

Δ = characteristic diffusion coefficient,

v = kinematic viscosity,

L = characteristic length,

h = characteristic depth,

U = characteristic velocity,

g = gravitational constant

ρ = water density

and ρ_p = particle density.

To use the reservoir transfer characteristic, or the probability of a specific sized particle to pass through the reservoir, the probability, p(D), of that size particle existing in the inflow must be known. The probability of the particle existing per unit volume in the inflow and the probability of the particle passage are dependent upon differnt causative factors and are, therefore, statistically independent. The probability of a specific size particle appearing in the outflow is the product of these two probabilties, t(D) p(D).

The fraction of material transferred through the reservoir is determined by integrating the probability of the particle distribution appearing in the outflow and in the inflow and ratioing these two quantities. The fraction trapped is found by subtracting the fraction passed from unit,

$$T = 1 - \left(\int_0^\infty t(D)p(D)dD \;/\; \int_0^\infty p(D)dD \right)$$

Since a characteristic length appears in the transfer characteristic, t(d), the trapped fraction may be computed at any point in the impoundment as well as the size distribution of the sediment deposited.

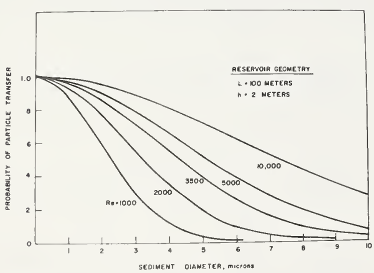

Figure 1.--Sediment Tranfer Function

As an example, an in-channel trap 100 m long and 2 m deep was evaluated. This is essentially a reach of a stream which has been widened and deepened. The transfer functions of figure 1 were derived from known textbook information for open channels flowing at low Reynolds numbers. Three different inflowing-particle-size distributions similar to that shown in figure 2 were assumed, and the trapping efficiencies calculated. These results are plotted on a Brune diagram shown in figure 3.

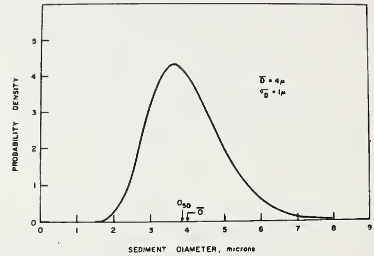

Figure 2.--Particle Size Distribution

The residence times for the calculated points shown range from 8 hours to 2.5 days. It is seen that relatively small changes in inflowing size distributions cause rather large changes in trap efficiences. From this first evaluation the conclusion is drawn that the Brune procedure for small reservoirs with short residence times is completely inadequate. The size distribution of the inflowing sediments play a dominant role in the trapping characteristics of the impoundment.

The new procedure derived in the paper is being developed from a number of simple shaped reservoirs whose flow characteristics can be determined. It is anticipated that the resulting analytic model can be added to the model FARMPND reported elsewhere in this volume.

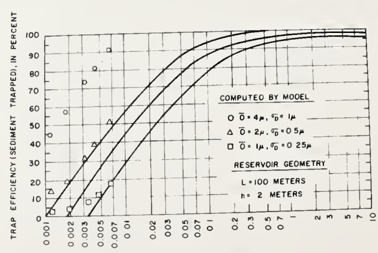

Figure 3.--Trap Efficiency of Reservoirs

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INSTREAM SEDIMENT ROUTING IN THE SWAM MODEL

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INTRODUCTION

Sediment moves because of hydrodynamic forces exerted on it by the flow of water. These forces are highly time dependent. The sediment transport model must, therefore, account for unsteadiness in sediment movement.

The dependence of sediment motion on flow conditions makes it sensitive to the longitudinal variations the flow experiences as a result of the stream boundary irregularities. That is reflected in the spatial variability of the sediment load distribution. Some particles may be carried primarily in suspension, while others move entirely as bed load. In addition, particles moving in suspension at one place may be moving as bed load further downstream. Whether a particular size fraction moves primarily as suspended or bed load, or in a mixed mode, determines to what extent that fraction of the sediment load will lag behind the flood wave and, therefore, the degree of longitudinal sorting. This necessitates that the transport model reflect the dependence of the sediment load lag on its material properties as well as on the hydraulic conditions.

Whenever the bed material consists of a mixture, its transport involves the motion of a multitude of particles of diverse sizes. Some particles may deposit on the streambed while others are scoured away, resulting in a size composition of the material in transport different from that of the bed. A realistic model must account for the interchange of particles between the bed layer and the moving load. During this particle interchange, the bed size composition changes continuously and, in the process, the bed may experience a net amount of aggradation or degradation. For certain flow conditions, the bed degradation in a reach may be limited by the formation of an armoring layer over which sediment may move either in suspension or as intermittent bed-load waves. The armoring layer may be destroyed during high flows and reformed at subsequent low flows. A model therefore must be capable of predicting the evolution of the streambed profile and the bed particle size distribution.

The sediment transport model used in the SWAM channel component is designed to meet the above criteria. The model can simulate the unsteady transport of sediment mixtures through a network of non-bifurcating channel reaches, and it is used in tandem with the SWAM flow routing model (Alonso 1983). Sediment movement is simulated using a variety of algorithms that operate on input data to generate output data reproducing the actual physical process. The balance of this paper discusses the most relevant features of the model formulation. A more detailed presentation is given by Borah et al. (1982a). Applications and testing of the model are reported by Borah et al. (1982b).

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MATHEMATICAL REPRESENTATION OF SEDIMENT TRANSPORT IN CHANNELS

Governing Equations

Movement of water and sediment in alluvial channels is described by the basic equations of conservation of mass and momentum, and by ancillary algorithms interrelating cross-sectional hydraulic properties, flow parameters, sediment load and load-bed interactions. In the most general form, these equations necessitate an exceedingly complex solution. Approximations are, therefore, introduced to reduce the formulation to a manageable level.

The phenomenon of sediment movement in stream channels is of course three-dimensional in nature, but the simulation of this complex phenomenon is at present not practical over long reaches of channels. Thus sediment transport, like water flow (Alonso 1983), is schematized as a one-dimensional phenomenon for the purpose of modeling.

Sediment transport and water flow are interrelated in such a way that they can never be completely disassociated. Experience has shown, however, that the typical time scale of water wave propagation phenomena is much shorter than the time scale of longitudinal bed changes (Vreugdenhil and deVries 1967). Although there are situations when the bed changes are nearly as rapid as free surface changes (Perdreau and Cunge 1971), this is not a common case. Accordingly, it is often possible to ignore flow transients during the simulation of bed processes. Conversely, deformation of alluvial beds within a short period of time are ordinarily much smaller than changes in the flow cross-sectional area. In addition, sediment load concentrations of up to 50,000 p/m will not change the density of the water-sediment mixture by more than 3 percent; thus, density variations may be safely ignored. In these instances, flood waves propagate unaffected by the erodibility of the bed and the presence of suspended sediment (Gradowczyk 1968). These criteria permit introduction of an uncoupled representation in which the equations of water continuity and momentum conservation are first used to compute new values of the flow variables independently of the sediment phase; then the sediment equations are used to update the sediment variables.

The formulation used in SWAM incorporates the above one-dimensional, uncoupled approximations, and it consists of the following system of equations:

Momentum equation for water:

$$h_{,x} - S_o + S_f = 0 \qquad (1)$$

Continuity equation for water:

$$Q_{,x} + A_{,t} = q_L \qquad (2)$$

Continuity equation for sediment in transport:

$$(AC)_{,t} + (Q_S)_{,x} = q_S - \delta + \eta \qquad (3)$$

Continuity equation for sediment stored in the bed:

$$(1 - \lambda)Wz_{,t} = \delta - \eta \qquad (4)$$

Potential transport capacity of flow:

$$T = f(Q,h,d,\ldots) \qquad (5)$$

where $Q(x,t)$ is the rate of water discharge, $A(x,t)$ is the flow area, $q_L(x,t)$ is the rate of lateral gain/loss per unit length, $h(x,t)$ is the flow depth, $S_o(x)$ is the longitudinal bed slope, $S_f(x,h)$ is the longitudinal friction slope, $C(x,t)$ is the volumetric concentration of the total sediment load, $q_S(x,t)$ is the volumetric rate of lateral sediment inflow per unit length, $\delta(x,t)$ is the volumetric rate of sediment settling per unit length, $\eta(x,t)$ is the volumetric rate of sediment entrainment per unit length, λ is the porosity of the bed material, W is the active bed width, $Q_S(x,t)$ is the volumetric rate of total load discharge, $z(x,t)$ is the active bed elevation, d is the sediment size, x is the longitudinal coordinate, and t is the time variable.

In equation 3 the longitudinal dispersion of suspended sediment was ignored because longitudinal dispersion in the suspended load zone is negligible in comparison to that due to storage in the bed. Since changes in bed geometries and overall load composition are of greater concern than exchanges between and distinguishing among the modes of transport in the different load zones, a further simplification was introduced by writing equation 3 in terms of the total load.

Bed erosion and sediment deposition cannot occur simultaneously at the same location. Nevertheless, in writing equation 3 it is recognized that, in general, entrainment is not the same as erosion, and settling is not the same as deposition. Entrainment is the rate at which detached bed particles are picked up by turbulent tractive forces and carried into the suspended load region. Settling is the rate at which suspended particles fall to the bed surface under the action of the gravitational pull. In any turbulent flow carrying sediment, there is always a continuous exchange of particles between the flow and the bed surface at any given location. Consequently, entrainment and settling can both take place simultaneously at a point even in those cases when sediment deposition or bed erosion do not occur along the channel. However, if settling exceeds entrainment, then net deposition occurs, and, conversely, when entrainment exceeds settling, net bed erosion takes place. Obviously, since entrainment cannot be both higher and lower than settling at the same time and location, it is impossible for both erosion and deposition to occur simultaneously at the same point. When settling equals entrainment, there can be neither erosion nor deposition and the transport process is in pseudoequilibrium at that point. The balance between η and δ will be denoted by

$$g_d = \eta - \delta \qquad (6)$$

where $g_d(x,t)$ represents sediment deposition ($g_d < 0$), bed erosion ($g_d > 0$), or pseudoequilibrium ($g_d = 0$).

The solution of equations 1 and 2 is discussed in a companion paper (Alonso 1983). The present paper is solely concerned with the treatment of equations 3 through 6, the sediment equations.

Expressing the volumetric concentration as $C = Q_S/Q$, and combining equations 2, 3, and 6 results in

$$AC_{,t} + QC_{,x} = q_S + g_d - q_L C. \qquad (7)$$

Equation 7 is a quasi-linear, hyperbolic equation governing the propagation of sediment load waves. These waves propagate along with the flood waves by riding the body of water as suspended or bed load. The celerity of sediment load waves is smaller, in general, than the celerity of the carrying flood wave. This celerity lag is strictly a function of local flow and sediment properties. It should not be confused with the differences sometimes observed between the time of arrival of the flow peak and sediment load peak, which mostly depends on external conditions.

Subsidiary Equations

Residual Transport Capacity

The amount of material transported or deposited in a channel reach is the result of the interaction of two processes: the transport capacity of the flow and the amount of sediment entering and moving through the reach. Imbalances between sediment supply and transport capacity cause aggradation or degradation of the channel bed. In order to track the onset and evolution of such imbalances a variable called residual transport capacity is introduced. This variable is defined as the ability of the stream to carry any additional amount of a particular size fraction in the presence of all the size fractions

already presented in the flow. The residual transport capacity is expressed as follows (Borah et al. 1982a):

$$T_{ri} = \Omega T_i;\ \Omega = 1 - \sum_{j=1}^{n} (C_j/T_j),\ i = 1,2,\ldots,n \qquad (8)$$

where n is the range of sediment size fractions. The summation term in equation 8 represents the fraction of T_i taken up by all the size fractions in transport. The quantity Ω is the remaining capacity available for transporting additional material of size d_i. Thus, $\Omega > 0$ identifies an eroding bed condition, while $\Omega < 0$ characterizes an aggrading bed condition. When $\Omega = 0$ there is no net load change and the transport process remains in pseudoequilibrium. By continuously tracking the value of Ω, the dependence of the individual residual capacities on the composition of the load, and the associated exchange between the sediment load and the bed are readily simulated.

Active bed layer thickness

In alluvial channels, the materials available for entrainment are essentially those exposed at the bed surface. As dunes and ripples move slowly downstream, they continuously mix all the sediment they contain. The space occupied by these bed features is thus regarded as a mixing zone below which the bed material remains undisturbed. During the scouring of bed materials, the exchange between bed and flow takes place in a thin layer at the bed surface, identified here as the "active layer." Several of these layers may be scoured away while the mixing zone is degrading. When the bed is armored, the last active layer becomes the armor coat. Conversely, during the process of bed aggradataion, several active layers will be deposited on the bed, forming a new mixing zone. To model this process, the mixing zone is pictured as a band of constant thickness divided into several layers, the layer in contact with the flow always being referred to as the active layer. The thickness of this layer is given by (Borah et al. 1982a):

$$\tau = 100\ d_L/[(1 - \lambda_L) \sum_{i=L}^{n} P_i] \qquad (9)$$

in which P_i is the percentage of the fraction i present in the layer, and L is the smallest fraction the flow cannot transport.

Volume erosion matrix

In order to account for the time evolution of the active layer thickness, it is necessary to continuously track the size composition of this layer. This is done by introducing an accounting procedure that essentially consists of monitoring the number and amount of material fractions that can be entrained whenever a given fraction is removed by the flow from the bed surface. Let V_j be the total volume of the d_j size present in the active layer per unit length of channel. Thus,

$$V_j = W\tau P_j(1 - \lambda_j)/100 \qquad (10)$$

Using this definition and the above accounting procedure, the following volume erosion matrix is defined:

$$e_{ij} = \varepsilon_j 2^{i-j-1} V_i V_j / \sum_{k=j}^{n} 2^{k-j-1} V_k \qquad (11)$$

in which e_{ij} is the volume of material fraction d_j that becomes available for entrainment when an exposed fraction d_i is eroded from the bed surface, and ε_j is an erodibility parameter. This parameter controls the amount of bed degradation and is calibrated by matching the computed sediment yield with observed values. The formulation and physical meaning of equation 11 are discussed by Borah et al. (1982a).

Initial and Boundary Conditions

The solution of equation 7 requires specification of initial and boundary conditions.

Initial conditions must be given along the channel reach in the form of known fraction load discharges and bed elevations. This information is either read from a previous SWAM simulation run or specified with some degree of approximation.

The uncoupled, hyperbolic character of equation 7 calls for only one upstream boundary condition. Consequently, discharges of sediment fractions as a function of time are imposed at the upstream end of the channel reach. Although knowledge of the upstream bed elevation as a function of time is not needed, SWAM preserves continuity of bed elevation at the junction between continuous reaches.

NUMERICAL ROUTING

The routing technique is based on a predictor-corrector method. In the predictor part the sediment equations are solved on a characteristic grid and an estimate of the sediment variables is obtained. In the corrector part these variables are adjusted with consideration given to the appropriate celerity lags of the individual sediment waves, which are ignored in the predictor part. Linear interpolation of the sediment variable values on the characteristic grid yields the corresponding values at the nodes of a rectangular grid consistent with the finite-difference grid used in the flow routing scheme.

In the predictor part, the quasi-linear hyperbolic equation 7 is solved by the method of characteristics assuming no celerity lag between the sediment and flood waves. Integrating between two points x_i and $x_j = x_i + \Delta x$ along the characteristic path, the following expression results for the sediment concentration distribution along the channel:

$$C_k(x_j,t_j) = C_k(x_i,t_i) + \frac{1}{Q(x_j,t_j)} \int_{x_i}^{x_j} q_{L,k}[\xi,t(\xi)]d\xi$$

$$+ \frac{1}{Q(x_j,t_j)} \int_{x_i}^{x_j} g_d[\xi,t(\xi)]d\xi \qquad (12)$$

$$t_j = t_i + \int_{x_i}^{x_j} \{U[\xi,t(\xi)]\}^{-1}d\xi \qquad (13)$$

where U is the mean flow velocity, k represents the sediment fraction, and Δx is the space increment between nodes of the rectangular grid.

The last integral in equation 12 represents the volume of either sediment deposition or erosion along the distance Δx. The sum of the first two terms on the RHS of equation 12 is substituted for C_j in equation 8. The sign of Ω determines the way in which the last integral in equation 12 is evaluated. Whenever $\Omega > 0$, erosion is conceptually simulated by depleting the elements of the erosion matrix, equation 11, one row at a time, beginning with the first row which corresponds to the smallest size fraction exposed at the bed surface. This process continues until either the residual transport capacity, $T_{r,k}$, is satisfied or the active layer becomes armored. When $\Omega < 0$, the model simulates deposition and settled material is added to the active layer. Deposition begins with the largest fraction and continues through the smaller fraction until either the stream is no longer overloaded ($\Omega = 0$) or all the fractions in transport have been deposited. Space limitations preclude a detailed presentation of the active layer treatment during bed aggrading and degrading modes. The details are given by Borah et al. 1982a.

During the corrector step the values computed above are adjusted to account for the correct celerities of the individual sediment waves. It is a recognized fact that the streamwise velocity of sediment particles always lag behind the velocity of water. This velocity lag ranges from negligible values of clay and silt particles in suspension, to quite large differences in the case of coarse sands and gravels moving as bed load. Accordingly, a correction based on transport mechanics considerations is applied to the travel time of sediment waves as follows:

$$t_j^* \cong t_i + \Delta x\{U(1-\beta)$$

$$+ 0.1\, \beta U^2 u_*^3/[h(S_k-1)^2 g^2 d_k^2(1-F_r^2)]\}^{-1}, \qquad (14)$$

$$\beta = \begin{cases} v_s/u_*, & v_s < u_* \\ 1\;\;\;\;\;, & v_x \geqq u_* \end{cases}$$

in which g is the acceleration of gravity, u_* is the bed shear velocity, F_r is the flow Froude number, v_s is the settling velocity of the sediment fraction, and S_k is the corresponding specific gravity. If the interval $t_j^* - t_i$ does not equal the time increment used in the rectangular grid, Δt, the above values of the sediment variables are linearly interpolated (or extrapolated) to obtain the values of these variables at the nodes of the rectangular grid. Thus, the new concentrations are

$$C_k(x_j,t_i+\Delta t) = C_k(x_i,t_i) \qquad (15)$$

$$+ [C_k(x_j,t_j)-C_k(x_i,t_i)]\Delta t/(t_j^*-t_i)$$

Summing the results over all sediment fractions gives the total sediment discharge:

$$Q_S(x_j,t_i + \Delta t) = Q(x_j,t_i + \Delta t) \sum_{k=1}^{n} C_k(x_j,t_i + \Delta t) \qquad (16)$$

and the local change in bed elevation (equation 4):

$$z(x_j,t_i+\Delta t) = z(x_j,t_i) \qquad (17)$$

$$+ \frac{1}{W}\frac{\Delta t}{t_j^*-t_i} \sum_{k=1}^{n} \frac{1}{1-\lambda_k} \int_{xi}^{x_j} gd[\xi,t(\xi)]d\xi$$

The above procedure is repeated all along the channel reach to its outlet in order to obtain the evolution of the total load composition, active bed layer composition, and longitudinal bed profile.

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SWRRB SEDIMENT ROUTING

J. R. Williams[1]

INTRODUCTION

A model called SWRRB (simulator for water resources in rural basins) was developed for simulating hydrologic and related processes in rural basins. The objective in model development was to predict the effect of management decisions on water and sediment yields with reasonable accuracy for ungauged rural basins throughout the United States. The three major components of SWRRB are weather, hydrology, and sedimentation. Processes considered include surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage, and sedimentation. More information about SWRRB is contained in two other papers in this volume. Williams and Nicks[2] give an overview of SWRRB, and Williams[2] describes the flood routing component.

SEDIMENT YIELD

Subbasin Yield

Sediment yield is computed for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt 1977).

$$Y = 11.8\,(V \times q_p)^{0.56}\,(K)\,(C)\,(PE)\,(LS) \tag{1}$$

where Y is the sediment yield from the subbasin in t, V is the surface runoff volume for the subbasin in m^3, q_p is the peak flow rate for the subbasin in m^3/s, K is the soil erodibility factor, C is the crop management factor, PE is the erosion control practice factor, and LS is the slope length and steepness factor.

The average land slope of a subbasin can be estimated with the grid-contour method (Williams and Berndt 1976) using the equations

$$S_d = (N_d)\,(CI) / LG_d \tag{2}$$

$$S = \sqrt{S_L^2 + S_W^2} \tag{3}$$

where S_d is the slope in one grid direction, N_d is the total number of contour crossings for grid lines in direction d, CI is the contour interval, LG_d is total length of grid lines within the subbasin in direction d in mm, S is the average slope of the subbasin in m/m, S_L is the slope in the length grid direction obtained from equation 2, and S_W is the slope in the width direction.

The average slope length is estimated for each subbasin with the contour-extreme point method (Williams and Berndt 1976) using the equation

$$\lambda = \frac{LC}{2\,EP} \tag{4}$$

where EP is the number of extreme points (channel crossings) on the contours, LC is the total length of all contours within the subbasin in m, and λ is the average slope length in m.

The LS factor is computed with the equation (Wischmeier and Smith 1978)

$$LS = \left(\frac{\lambda}{22.1}\right)^{\xi}\,(65.41S^2 + 4.56S + .065) \tag{5}$$

The exponent ξ varies with slope and is computed in SWRRB with the equation

$$\xi = 0.6\,(1 - \exp\,(35.835S)) \tag{6}$$

The value of the C factor for each crop is determined for each month from tables prepared by Wischmeier and Smith (1978). Values of the K and PE factors can be estimated for each subbasin using information contained in Technical Release No. 51 (USDA, Soil Conservation Service 1975).

SEDIMENT ROUTING

Ponds and Reservoirs

Inflow sediment yield to ponds and reservoirs (P/R) is computed with MUSLE as described in the subbasin yield section. The outflow from P/R is calculated with the equation

$$Y = (c_o)\,(QO)\,, \qquad QO > 0. \tag{7}$$

$$Y = 0.\,, \qquad QO = 0.$$

where Y is the P/R outflow sediment yield in t, c_o is the outflow sediment concentration in t/m^3, and QO is the outflow in m^3. The outflow concentration is a function of the P/R concentration at the beginning and end of the day.

$$c_o = (c_{S_1} + c_{S_2}) / 2 \tag{8}$$

where c_{S_1} and c_{S_2} are the are the P/R concentrations at the beginning and end of a day in t/m^3.

The initial P/R concentration is input to SWRRB. The inflow concentration can be calculated since Y and Q are simulated, but the final P/R concentration is unknown. It can be computed using the continuity equation

$$VM_2\,c_{S_2} = VM_1\,c_{S_1} + QI\,c_I - QO\,c_o \tag{9}$$

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[2]Williams, J. R., 1984, SWRRB flood routing. Proc. Natural Resources Modeling Symp., Ft. Collins, CO, October 1984; and Williams, J. R., and Nicks, A. D., 1984, SWRRB, A simulator for water resources in rural basins. Submitted to J. Hydraulics Div., ASCE, respectively.

where VM_1 and VM_2 are the P/R storage volumes at the beginning and end of a day in m^3, QI is the inflow volume in m^3, and c_I is the inflow concentration in t/m^3. Substituting equation 8 into equation 9 and rearranging yields an expression for the final concentration

$$c_{S_1} = \frac{VM_1 c_{S_1} + QI\, c_I - \frac{QO}{2} c_{S_1}}{VM_2 + \frac{QO}{2}} \qquad (10)$$

Between storms the final P/R concentration decreases to an equilibrium concentration according to the equation

$$c_S = (c_{S_2} - c_{Se}) \exp(-k_s \bullet t \bullet D50) + c_{Se} \qquad (11)$$

where c_S is the P/R concentration t days after the value of c_{S_2} is obtained, k_s is the decay constant, D50 is the median particle size of the inflow sediment in µm, and c_{Se} is the equilibrium P/R sediment concentration (input to SWRRB). The constant k_s is evaluated by assuming that 99 percent of the 1-µm particles are settled within 25 days (k_s = 0.184).

Channel and Floodplain

The channel and floodplain routing model is composed of two components operating simultaneously (deposition and degradation). The deposition equation is

$$c_{DP} = c_I \exp(-k_d \bullet FT \bullet \sqrt{D50}) \qquad (12)$$

where c_{DP} is the concentration of sediment after deposition between a subbasin outlet and the basin outlet, c_I is subbasin outflow sediment concentration, k_d is the deposition constant (~0.01), FT is the travel time from the subbasin outlet to the basin outlet, and D50 is the median particle size of the subbasin sediment yield in µm.

The degradation equation is

$$c_{DG} = (c_u - c_I)(1 - \exp(-k_e \bullet FT \bullet q_p / \sqrt{D50})) \qquad (13)$$

where c_{DG} is the concentration of sediment after reentrainment of deposited sediment plus channel and floodplain degradation, c_u is the upper limit of sediment concentration in flow (~0.25 t/m^3), k_e is the degradation constant (~2.788 X 10^{-4}), and q_p is the subbasin peak flow rate expressed in mm/h. The resulting basin outflow concentration is obtained by summing the results of equations 12 and 13.

$$c_O = c_{DP} + c_{DG} \qquad (14)$$

Basin sediment yield is the product of sediment concentration, c_O, and outflow volume, Q.

The sediment routing function (equations 12 and 13) provides a simple mechanism for transporting sediment in a realistic manner. Deposition is greatest for high concentrations of large-size sediment flowing for long time periods. Conversely, degradation will usually be insignificant for these conditions. Degradation becomes dominant when relatively clear water flows with high rates for long time periods. Reentrainment of previously deposited particles is greater when the particle size is small.

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